



CMS-BPH-21-004

CERN-EP-2021-215
2023/02/14

Observation of triple J/ψ meson production in proton-proton collisions

The CMS Collaboration^{*}

Abstract

Protons consist of three valence quarks, two up-quarks and one down-quark, held together by gluons and a sea of quark-antiquark pairs. Collectively, quarks and gluons are referred to as partons. In a proton-proton collision, typically only one parton of each proton undergoes a hard scattering – referred to as single-parton scattering – leaving the remainder of each proton only slightly disturbed. Here, we report the study of double- and triple-parton scatterings through the simultaneous production of three J/ψ mesons, which consist of a charm quark-antiquark pair, in proton-proton collisions recorded with the CMS experiment at the Large Hadron Collider. We observed this process – reconstructed through the decays of J/ψ mesons into pairs of oppositely charged muons – with a statistical significance above five standard deviations. We measured the inclusive fiducial cross section to be 272^{+141}_{-104} (stat) ± 17 (syst) fb, and compared it to theoretical expectations for triple- J/ψ meson production in single-, double- and triple-parton scattering scenarios. Assuming factorization of multiple hard-scattering probabilities in terms of single-parton scattering cross sections, double- and triple-parton scattering are the dominant contributions for the measured process.

Published in Nature Physics as doi:10.1038/s41567-022-01838-y.

High-energy particle accelerators are unique tools to study the structure of matter at the shortest distances. The most powerful accelerator today is the CERN Large Hadron Collider (LHC) that has so far collided beams of protons with energies of up to 6.5 TeV, resulting in center-of-mass energies of up to 13 TeV. Protons are used in energy-frontier colliders because they are relatively easy to accelerate and keep in a circular orbit to enable high collision rates. However, they are not fundamental particles and, in fact, have a complicated quantum mechanical structure. Protons consist of three quarks, two up-type and one down-type, and gluons, which hold together the three valence quarks, as well as of a “sea” of virtual quark-antiquark pairs, which are fundamental elements of the quantum vacuum. All these components are referred to as “partons”. In the standard picture of proton-proton (pp) collisions, typically only a few partons undergo a hard scattering with one another, with the remainders of each proton only slightly disturbed in the process. As the collision energy increases, the densities of gluons and sea quarks probed inside each proton grow rapidly. Thus, at high enough energies, more than one pair of partons can undergo a hard scattering in a single pp collision, leading to the simultaneous and independent production of two or more particles with transverse momentum (p_T) and/or mass (m) above a few GeV. Double-parton scatterings (DPS) were first observed at the CERN Intersecting Storage Rings some 35 years ago [1, 2] and have been a subject of intense theoretical and experimental investigations ever since [3]. Numerous DPS processes have been studied in measurements with many combinations of pairs of heavy and/or high- p_T produced particles [3]. Triple-parton scatterings (TPS), where three hard parton interactions take place simultaneously, have only been proposed for study recently [4] and have not been experimentally explored yet.

Studies of n -parton scattering (NPS) processes are important to elucidate the complicated inner structure of the proton and its evolution with energy [5, 6]. Many of these features, e.g., the parton density profile in the plane transverse to the colliding beams, as well as the various correlations (in position, momentum, flavor, color, spin, etc.) between individual partons, are very difficult to calculate theoretically, and can only be mapped out through experimental studies of NPS in different systems and for different numbers n of simultaneous scatterings [3]. Measurements of such processes not only allow for a deeper understanding of the proton structure, but are also of relevance at the LHC to predict backgrounds in rare standard model processes, and in searches for new physics, in final states where multiple heavy particles are produced [7, 8]. This work presents the experimental study of the simultaneous production of three massive particles originating in NPS, and the observation of triple-J/ ψ meson production. The study of TPS via triple-J/ ψ production provides input for further theoretical and experimental progress in understanding the NPS dynamics.

In the simplest approach, ignoring any correlations between the individual partons, the probability to produce n high- p_T particles in a given pp collision must be proportional to the n^{th} -product of probabilities to independently produce each of them. Thus, the probability to produce two or three high- p_T particles in DPS and TPS scales with the square and cube, respectively, of the corresponding single-parton scattering (SPS) probabilities [9]. The occurrence of DPS and TPS processes is therefore more likely for final states with large SPS cross sections, such as quarkonia states (e.g., J/ ψ and Y mesons), than for rarer heavier particles such as, e.g., electroweak (EW) bosons [10]. In the DPS case, the cross section to produce, e.g., two charmonium mesons ψ_1 and ψ_2 can be written as the product of the SPS cross sections for the production of each individual meson divided by an effective cross section to warrant the proper units of the final result,

$$\sigma_{\text{DPS}}^{\text{pp} \rightarrow \psi_1 \psi_2 + X} = \left(\frac{m}{2} \right) \frac{\sigma_{\text{SPS}}^{\text{pp} \rightarrow \psi_1 + X} \sigma_{\text{SPS}}^{\text{pp} \rightarrow \psi_2 + X}}{\sigma_{\text{eff}, \text{DPS}}} \quad (1)$$

Here, m is a combinatorial factor to avoid double counting, $m = 1$ (2) if $\psi_1 = \psi_2$ ($\psi_1 \neq \psi_2$), and $\sigma_{\text{eff,DPS}}$ is an effective cross section that, in a purely geometric approach, can be determined from the pp transverse overlap [9]. A *smaller* value of $\sigma_{\text{eff,DPS}}$, which is proportional to the average (squared) transverse separation of the partons participating in the two hard scatterings, implies *larger* DPS yields.

For the proton form factors typically implemented in the PYTHIA 8 [11] and HERWIG++ [12] event generators commonly used in collider physics, values of $\sigma_{\text{eff,DPS}} \approx 20\text{--}30\text{ mb}$ are expected. Such estimates are, however, about a factor of two larger than those experimentally derived via the ratio $\sigma_{\text{eff,DPS}} = (\sigma_{\text{SPS}}^{\text{pp} \rightarrow X_1} \sigma_{\text{SPS}}^{\text{pp} \rightarrow X_2}) / \sigma_{\text{DPS}}^{\text{pp} \rightarrow X_1 X_2}$ for processes involving pairs of high- p_T jets and/or EW bosons, which are found to lie in the range $\sigma_{\text{eff,DPS}} \approx 10\text{--}20\text{ mb}$ [13–19]. This discrepancy has been mostly explained as evidence of parton correlations in the collision not accounted for in the purely geometrical approaches [20]. In addition, significantly lower $\sigma_{\text{eff,DPS}} \approx 3\text{--}10\text{ mb}$ values have been extracted from measurements of quarkonium pair production ($J/\psi J/\psi$ [21–25], $J/\psi Y$ [26], and YY [8, 27]) that have been interpreted as due to the different dominant species (mostly gluons for quarkonia, and quarks for EW bosons) in the parton distribution functions (PDFs) probed in the different scatterings [3], but can be also attributed in some cases to poorly controlled subtractions of SPS contributions [10].

The study of TPS via triple- J/ψ production can help solve all the issues mentioned above. The equivalent of Eq. (1) for the production of three charmonium mesons in a TPS process reads

$$\sigma_{\text{TPS}}^{\text{pp} \rightarrow \psi_1 \psi_2 \psi_3 + X} = \left(\frac{m}{3!} \right) \frac{\sigma_{\text{SPS}}^{\text{pp} \rightarrow \psi_1 + X} \sigma_{\text{SPS}}^{\text{pp} \rightarrow \psi_2 + X} \sigma_{\text{SPS}}^{\text{pp} \rightarrow \psi_3 + X}}{\sigma_{\text{eff,TPS}}^2}, \quad (2)$$

where $m = 1, 3$, or 6 (depending on whether all three, two, or none of the ψ_i states are identical). In the absence of parton correlations, the effective cross section $\sigma_{\text{eff,TPS}}$ is closely related to its DPS counterpart via $\sigma_{\text{eff,TPS}} = \kappa \sigma_{\text{eff,DPS}}$, with κ of order unity. A value of $\kappa = 0.82 \pm 0.11$ has been derived in [4] for a variety of proton transverse parton profiles. A theoretical study of the production of three prompt- J/ψ mesons [28], based on the nonrelativistic quantum chromodynamics (NRQCD) approach at leading-order (LO) accuracy as implemented in the HELAC-ONIA code [29, 30], has demonstrated that the pure SPS contributions are negligible compared to those from DPS and TPS. Namely, the upper left diagram of Fig. 1 is irrelevant compared to the two other diagrams in the left column of the figure. The experimental measurement of $pp \rightarrow J/\psi J/\psi J/\psi X$ is thus a golden channel for the study of TPS and, in addition, provides an alternative extraction of $\sigma_{\text{eff,DPS}}$, thereby shedding light on the underlying dynamics of hard NPS. The production of J/ψ states can also proceed nonpromptly through the decay of a beauty-quark (b) hadron. Notwithstanding a small branching fraction, $\mathcal{B}_{b \rightarrow J/\psi X} \approx 1\%$ [31], the cross section to produce $b\bar{b}$ pairs is large at the LHC, $\sigma(pp \rightarrow b\bar{b} X) \approx 0.5\text{ mb}$ [4]. The contributions of such processes to inclusive triple- J/ψ production are schematically shown in Fig. 1 (diagrams to the right of the vertical dashed line).

This Letter reports the observation of the simultaneous production of three J/ψ mesons in pp collisions. The analysis is based on a data sample collected at $\sqrt{s} = 13\text{ TeV}$ by the CMS experiment, corresponding to an integrated luminosity of 133 fb^{-1} . The J/ψ mesons are reconstructed in their dimuon decay mode over a fiducial phase space in transverse momenta and (pseudo)rapidities ($p_T^{\mu, J/\psi}$, $|\eta^\mu|$, and $|y^{J/\psi}|$) defined to maximize the signal purity and the detector acceptance and efficiency. The analysis of the 6μ final state offers a very clean experimental signature for inclusive triple- J/ψ production, comprising prompt and nonprompt components. The Methods section provides more details on the experimental setup and event reconstruction.

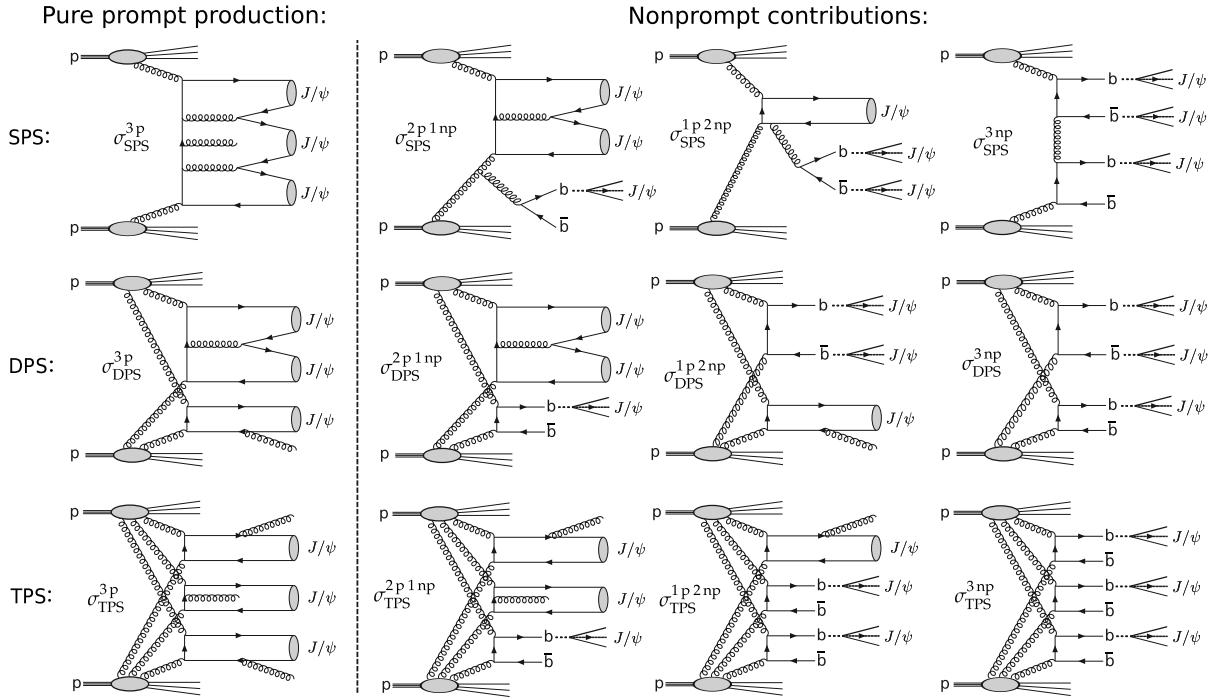


Figure 1: Leading-order diagrams for inclusive triple- J/ψ production in pp collisions. The SPS, DPS, and TPS processes are depicted in the top, middle, and bottom row, respectively. The leftmost diagrams show triple prompt- J/ψ processes. The remaining diagrams show (left to right) final states with increasing contributions of nonprompt J/ψ mesons from beauty hadron decays. Curly lines indicate gluons, arrows (anti)charm quarks, and blobs the proton parton densities. The symbols $\sigma_{\text{NPS}}^{ipjnp}$ identify the number (i and j) of prompt (p) and nonprompt (np) contributions to the cross section of each diagram.

The signal yield is extracted with a three-dimensional unbinned extended maximum likelihood fit of the $m_{\mu^+\mu^-}$ distributions of all J/ψ candidates in the event over the $2.9 < m_{\mu^+\mu^-} < 3.3 \text{ GeV}$ range. The expected J/ψ mass peaks are modeled with a Gaussian function with mean fixed to their nominal value ($m^{J/\psi} = 3.097 \text{ GeV}$) [31] and the root-mean-square (RMS) width fixed to the resolution derived from the MC simulation ($\sigma_m \approx 30 \text{ MeV}$). Given the very low number of events passing the selection, the mass mean and RMS width of the J/ψ mesons cannot be left as free parameters in the fit. The dimuon background is described with an exponential function [23, 32–35]. The fit has eight free parameters for the yields given by the combination of each of the three J/ψ candidates as being either signal or background. The extracted signal yield (red shaded areas in the $m_{\mu^+\mu^-}$ distributions of Fig. 2) corresponds to $N_{\text{sig}}^{3J/\psi} = 5.0^{+2.6}_{-1.9}$ triple- J/ψ events, with $1.0^{+1.4}_{-0.8}$ background events. The statistical significance of the signal is evaluated using various methods. From the likelihood ratio of two fits (background-only imposing $N_{\text{sig}}^{3J/\psi} = 0$, and the default signal-plus-background), with the standard asymptotic formula [36] assuming that the conditions to apply Wilks’ theorem [37] are satisfied, a significance of 6.7 standard deviations (std. dev.) is obtained. The significance derived assuming a Poisson counting experiment yields 5.8 std. dev., and it is found to be above 5.5 std. dev. by using MC pseudoexperiments.

To cross-check the size of the combinatorial background derived from the fit, two tests are carried out. First, the fit is repeated over the extended dimuon mass range [2.5–3.3] GeV for the two subleading J/ψ mesons (dotted curves in Fig. 2). This mass range corresponds to an asym-

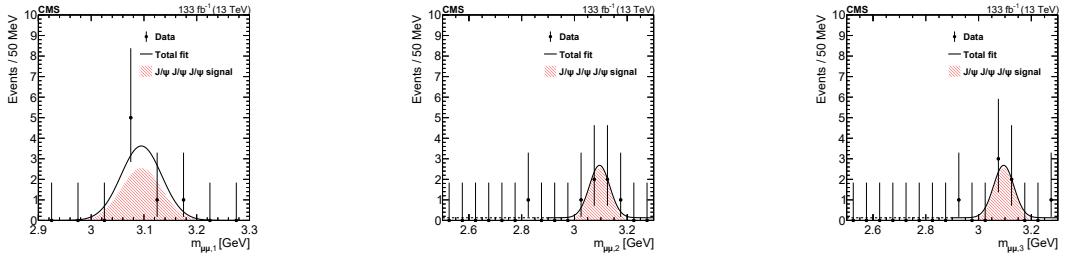


Figure 2: Invariant mass distributions for the three $\mu^+\mu^-$ pairs in the selected events. The three distributions are ordered, left to right, by decreasing pair p_T . The data are represented by the points with the vertical bars showing the (Poisson) statistical uncertainties. The solid (dotted) curve shows the overall fit to the data (in the extended mass range, discussed in the main text), and the red shaded area the fitted signal yield. The horizontal bin width is indicated on the vertical axis legend.

metric window of about $[-20\sigma_m, +7\sigma_m]$ around the J/ψ nominal mass that, as aforementioned, covers lower dimuon masses where the background, if any, should be larger. The obtained signal yield is fully consistent with the default result. A second test is performed whereby the opposite-sign (OS) requirement is removed to allow also for same-sign dimuon combinations ($\mu^\pm\mu^\pm$) for the two subleading pairs. After applying the rest of the selection criteria of the default analysis, no triplet events containing same-sign muon pairs are observed.

In order to estimate the average prompt and nonprompt contributions in the triple- J/ψ events, the proper decay-length of each J/ψ is calculated as $L^{J/\psi} = (m^{J/\psi}/p_T^{J/\psi}) L_{xy}^{J/\psi}$, where $L_{xy}^{J/\psi} = (\vec{r} \cdot \vec{p}_T^{J/\psi}) / |\vec{p}_T^{J/\psi}|$ is the transverse distance between the J/ψ decay vertex and the PV (\vec{r} is the vector from the PV to the J/ψ vertex). The experimental resolution on $L^{J/\psi}$ is $\approx 20\ \mu\text{m}$. Prompt J/ψ mesons are defined as those having $L^{J/\psi} < 60\ \mu\text{m}$, a choice that reduces the nonprompt contribution by more than one order in magnitude [33]. A signal-only subset of events is defined based on all J/ψ candidates found in a narrower invariant mass region, within ± 3 std. dev. around $m^{J/\psi}$, than that used in the default signal extraction. In this range, five triple- J/ψ events are found that can be classified as two events being consistent with the “2 nonprompt + 1 prompt J/ψ ” hypothesis, and one event each in the “1 nonprompt + 2 prompt J/ψ ”, “3 nonprompt J/ψ ”, and “3 prompt J/ψ ” categories. Such a classification is confirmed with a second method where prompt and nonprompt weights are extracted with the SPLOT technique [38], exploiting an unbinned maximum likelihood fit of the $L^{J/\psi}$ distributions.

The cross section for inclusive triple- J/ψ production measured in the fiducial region defined in Table 1 is obtained via $\sigma(pp \rightarrow J/\psi J/\psi J/\psi X) = N_{\text{sig}}^{3J/\psi} / (\epsilon \mathcal{L}_{\text{int}} \mathcal{B}_{J/\psi \rightarrow \mu^+ \mu^-}^3)$, where $N_{\text{sig}}^{3J/\psi}$ is the number of signal events, \mathcal{L}_{int} the total integrated luminosity, $\mathcal{B}_{J/\psi \rightarrow \mu^+ \mu^-}$ the dimuon branching fraction, and $\epsilon = \epsilon_{\text{trig}} \epsilon_{\text{id}} \epsilon_{\text{reco}}$ the total efficiency composed of trigger, identification, and reconstruction components. The J/ψ muon identification and reconstruction efficiencies are extracted with the tag-and-probe method using correction factors from the large inclusive $J/\psi \rightarrow \mu^+\mu^-$ data samples used in Ref. [39]. Since they depend on the p_T and η of the muons, they propagate into the final cross section via two-dimensional maps, yielding $\epsilon_{\text{id}} \epsilon_{\text{reco}} = 0.78$. The trigger efficiency is found to be $\epsilon_{\text{trig}} = 0.84$ from a study of the MC samples.

The impact on the extracted cross section of the choice of functions used to reproduce the shapes of the signal and background dimuon invariant masses is studied. For the signal, the Gaussian distribution is changed to a Crystal-Ball function [40] as well as to a Gaussian function with the RMS width left to vary in the fit. The background shape is changed from

Table 1: Fiducial phase space for the triple-J/ ψ cross section measurement.

For all muons	$p_T > 3.5 \text{ GeV}$ for $ \eta < 1.2$
	$p_T > 2.5 \text{ GeV}$ for $1.2 < \eta < 2.4$
For all J/ ψ mesons	$p_T > 6 \text{ GeV}$ and $ y < 2.4$ $2.9 < m_{\mu^+\mu^-} < 3.3 \text{ GeV}$

the default exponential to first- and zeroth-order polynomials. The relative differences in the cross sections obtained from the alternative modeling for signal and background are 0.8 and 3.4%, respectively, and are assigned as corresponding systematic uncertainties. Uncertainties arising from the muon reconstruction and identification efficiencies are derived by allowing the tag-and-probe correction factors for each (p_T, η) bin to vary within their precision, and checking the effect on the extracted cross section. The maximal variation observed is $\pm 1.0\%$. Varying the relative composition of double- and single-J/ ψ meson production in the MC event sample used for the determination of the trigger efficiency leads to a 3.4% propagated uncertainty. Uncertainties of 1.6% and 3.0% are added from the integrated luminosity measurement [41–43], and from the simulated signal sample size, respectively. The uncertainty in the $\mathcal{B}_{J/\psi \rightarrow \mu^+\mu^-} = (5.961 \pm 0.033)\%$ value [31] propagates into a 1.7% uncertainty in the cross section. The total systematic uncertainty of the measured cross section is 6.2%, obtained by adding all individual sources in quadrature (Extended Data Table 5). The measured cross section for triple-J/ ψ production, within the fiducial region defined in Table 1, is $\sigma(pp \rightarrow J/\psi J/\psi J/\psi X) = 272^{+141}_{-104}$ (stat) ± 17 (syst) fb.

The total inclusive triple-J/ ψ cross section is expected to correspond to the sum of the contributions from the SPS, DPS, and TPS processes schematically shown in Fig. 1, each of which contains various combinations of prompt (p) and nonprompt (np) J/ ψ contributions,

$$\begin{aligned} \sigma_{\text{tot}}^{3J/\psi} &= \sigma_{\text{SPS}}^{3J/\psi} + \sigma_{\text{DPS}}^{3J/\psi} + \sigma_{\text{TPS}}^{3J/\psi} \\ &= (\sigma_{\text{SPS}}^{3p} + \sigma_{\text{SPS}}^{2p1np} + \sigma_{\text{SPS}}^{1p2np} + \sigma_{\text{SPS}}^{3np}) \\ &\quad + (\sigma_{\text{DPS}}^{3p} + \sigma_{\text{DPS}}^{2p1np} + \sigma_{\text{DPS}}^{1p2np} + \sigma_{\text{DPS}}^{3np}) + (\sigma_{\text{TPS}}^{3p} + \sigma_{\text{TPS}}^{2p1np} + \sigma_{\text{TPS}}^{1p2np} + \sigma_{\text{TPS}}^{3np}). \end{aligned} \quad (3)$$

Under the simplest assumption of factorization of multiple hard-scattering probabilities in terms of SPS cross sections, the DPS and TPS contributions to triple-J/ ψ production (last row of Eq. (3)) can be written through Eqs. (1) and (2) as a combination of products of single- and double-J/ ψ SPS cross sections as

$$\sigma_{\text{DPS}}^{3J/\psi} = \frac{\mathfrak{m}_1}{\sigma_{\text{eff},\text{DPS}}} \left[\sigma_{\text{SPS}}^{2p} \sigma_{\text{SPS}}^{1p} + \sigma_{\text{SPS}}^{2p} \sigma_{\text{SPS}}^{1np} + \sigma_{\text{SPS}}^{1p} \sigma_{\text{SPS}}^{1p1np} + \sigma_{\text{SPS}}^{1p1np} \sigma_{\text{SPS}}^{1np} + \sigma_{\text{SPS}}^{1p} \sigma_{\text{SPS}}^{2np} + \sigma_{\text{SPS}}^{2np} \sigma_{\text{SPS}}^{1np} \right], \quad (4)$$

and

$$\sigma_{\text{TPS}}^{3J/\psi} = \frac{\mathfrak{m}_3}{\sigma_{\text{eff},\text{TPS}}^2} \left[\left(\sigma_{\text{SPS}}^{1p} \right)^3 + \left(\sigma_{\text{SPS}}^{1np} \right)^3 \right] + \frac{\mathfrak{m}_2}{\sigma_{\text{eff},\text{TPS}}^2} \left[\left(\sigma_{\text{SPS}}^{1p} \right)^2 \sigma_{\text{SPS}}^{1np} + \sigma_{\text{SPS}}^{1p} \left(\sigma_{\text{SPS}}^{1np} \right)^2 \right], \quad (5)$$

with combinatorial prefactors $\mathfrak{m}_1 = 2/2 = 1$, $\mathfrak{m}_2 = 3/3! = 1/2$, and $\mathfrak{m}_3 = 1/3! = 1/6$. Therefore, from the eight individual SPS cross sections for single-, double-, and triple-J/ ψ production, one can determine the total triple-J/ ψ production cross section via Eqs. (3–5). The values of the relevant SPS cross sections, each within the fiducial phase space defined in Table 1, are computed as described next and listed in Table 2.

Table 2: Theoretical J/ψ , $J/\psi + J/\psi$, and $J/\psi + J/\psi + J/\psi$ cross sections. Predictions for single-, double-, and triple- J/ψ production cross sections in SPS processes, which pass the fiducial criteria listed in Table 1, derived from the HELAC-ONIA (HO) and MADGRAPH5_aMC@NLO (MG5NLO) matrix element calculators, complemented with the PYTHIA 8 (PY8) parton shower, as described in the text.

SPS single- J/ψ production		SPS double- J/ψ production			SPS triple- J/ψ production			
HO(DATA)	MG5NLO+PY8	HO(NLO*)	HO(LO)+PY8	MG5NLO+PY8	HO(LO)	HO(LO)+PY8	HO(LO)+PY8	MG5NLO+PY8
$\sigma_{\text{SPS}}^{1\text{p}}$ $570 \pm 57 \text{ nb}$	$\sigma_{\text{SPS}}^{1\text{np}}$ $600^{+130}_{-220} \text{ nb}$	$\sigma_{\text{SPS}}^{2\text{p}}$ $40^{+80}_{-26} \text{ pb}$	$\sigma_{\text{SPS}}^{1\text{p}1\text{np}}$ $24^{+35}_{-16} \text{ fb}$	$\sigma_{\text{SPS}}^{2\text{np}}$ $430^{+95}_{-130} \text{ pb}$	$\sigma_{\text{SPS}}^{3\text{p}}$ $< 5 \text{ ab}$	$\sigma_{\text{SPS}}^{2\text{p}1\text{np}}$ $5.2^{+9.6}_{-3.3} \text{ fb}$	$\sigma_{\text{SPS}}^{1\text{p}2\text{np}}$ 14^{+17}_{-8} ab	$\sigma_{\text{SPS}}^{3\text{np}}$ $12 \pm 4 \text{ fb}$

The values of the SPS single, double, and triple prompt- J/ψ cross sections ($\sigma_{\text{SPS}}^{1\text{p}}$, $\sigma_{\text{SPS}}^{2\text{p}}$, $\sigma_{\text{SPS}}^{3\text{p}}$) are obtained with HELAC-ONIA at LO or at approximately next-to-leading-order (NLO*) accuracy [44, 45]. For the single prompt- J/ψ prediction ($\sigma_{\text{SPS}}^{1\text{p}}$), the theoretical calculations HO(DATA) in Table 2 are normalized with a parameterization [46] that reproduces the data measured in pp collisions at 7 TeV [34, 47], including all feed-down contributions from decays of heavier charmonium resonances. For the double and triple prompt- J/ψ processes, the HELAC-ONIA calculations include only the $\psi(2S)$ feed-down because the χ_c decay contribution is only a few percent. All predictions for cross sections of nonprompt J/ψ meson production in beauty hadron decays ($\sigma_{\text{SPS}}^{1\text{np}}$, $\sigma_{\text{SPS}}^{2\text{np}}$, $\sigma_{\text{SPS}}^{3\text{np}}$) have been obtained with MADGRAPH5_aMC@NLO (v.2.6.6) [48] matrix elements, scaled by a factor of 1.15 to account for next-to-next-to-leading-order $b\bar{b}$ cross section corrections [4], combined with the PYTHIA 8.244 generator for parton shower and decays (including all feed-down quarkonium contributions) [45]. Mixed prompt plus nonprompt cross sections ($\sigma_{\text{SPS}}^{\text{XpYn}}$) are obtained from $J/\psi + b\bar{b}$ events generated with HELAC-ONIA at LO in the color-singlet model interfaced with PYTHIA 8.244 for the b-quarks fragmentation into non-prompt J/ψ mesons. The uncertainties include the (dominant) theoretical scale dependence and the (subdominant) PDF uncertainties of the CT14NLO set [49], except for the single prompt- J/ψ predictions that have a better precision because they are determined with an explicit fit of the NRQCD predictions to the LHC data [46] and have an associated 10% uncertainty of experimental origin. All these sources are treated as uncorrelated and the corresponding uncertainties are added in quadrature.

Using Eqs. (4,5) with the SPS cross sections listed in Table 2, and assuming that the effective DPS and TPS cross sections are related by $\sigma_{\text{eff,TPS}} = (0.82 \pm 0.11) \sigma_{\text{eff,DPS}}$ [4] in a baseline approach that ignores parton correlations, one can extract the value of the effective DPS cross section that yields the experimentally measured $\sigma_{\text{tot}}^{3J/\psi}$ value. Following such a procedure, the value $\sigma_{\text{eff,DPS}} = 2.7^{+1.4}_{-1.0} (\text{exp})^{+1.5}_{-1.0} (\text{theo}) \text{ mb}$ is derived, where the first uncertainty is due to the experimental $\sigma_{\text{tot}}^{3J/\psi}$ precision and the second is due to the propagation of all sources of theoretical uncertainties in the ingredients of Eqs. (3–5).

The inclusive triple- J/ψ theoretical cross sections and yields for each individual process contributing to the total production are listed in Table 3. The expected contributions from SPS, DPS, and TPS processes to the total triple- J/ψ cross section amount to about 6, 74, and 20%, respectively. This confirms the conclusion of Ref. [28] that triple- J/ψ production is a golden channel to study DPS and TPS, with minimal SPS contamination. The largest contributors to the triple- J/ψ cross section are $\sigma_{\text{DPS}}^{3\text{np}}$ and $\sigma_{\text{DPS}}^{1\text{p}2\text{np}}$, accounting for $\approx 33\%$ each, $\sigma_{\text{TPS}}^{2\text{p}1\text{np}}$ and $\sigma_{\text{TPS}}^{1\text{p}2\text{np}}$ amounting to about 7% each, and $\sigma_{\text{SPS}}^{3\text{np}}$ representing about 4% of the total production. In terms of prompt and nonprompt contributions, the theoretical expectation for the production of three promptly produced J/ψ mesons is $\approx 5\%$ of the total yield, whereas the percentage expected for

Table 3: Expected contributions to triple-J/ ψ production. Central values of the predictions for triple-J/ ψ production cross sections (in fb) and yields from SPS, DPS (for $\sigma_{\text{eff},\text{DPS}} = 2.7 \text{ mb}$), and TPS (for $\sigma_{\text{eff},\text{TPS}} = 0.82 \sigma_{\text{eff},\text{DPS}} = 2.2 \text{ mb}$) processes, and their total sum. The values are given in columns for combinations of n prompt and $(3 - n)$ nonprompt J/ ψ mesons, the last column giving their corresponding sums. The DPS and TPS results are derived via Eqs. (3–5) from the SPS cross sections listed in Table 2 with $\sigma_{\text{eff},\text{DPS}}$ chosen so that the sum of contributions yields a total cross section equal to the experimental value of $\sigma_{\text{tot}}^{\text{3J}/\psi}$. The expected yield, $N_{\text{NPS}}^{\text{3J}/\psi}$, is given for an effective integrated luminosity of $\epsilon \mathcal{L}_{\text{int}} = 87 \text{ fb}^{-1}$ for each contributing process. The last column lists the total cross sections and yields for SPS, DPS, TPS and their sums.

Process:	3 prompt	2 prompt+1 nonprompt	1 prompt+2 nonprompt	3 nonprompt	Total
$\sigma_{\text{SPS}}^{\text{3J}/\psi}$ (fb)	<0.005	5.7	0.014	12	18
$N_{\text{SPS}}^{\text{3J}/\psi}$	0.0	0.10	0.0	0.22	0.32
$\sigma_{\text{DPS}}^{\text{3J}/\psi}$ (fb)	8.4	8.9	90	95	202
$N_{\text{DPS}}^{\text{3J}/\psi}$	0.15	0.16	1.65	1.75	3.7
$\sigma_{\text{TPS}}^{\text{3J}/\psi}$ (fb)	6.1	19.4	20.4	7.2	53
$N_{\text{TPS}}^{\text{3J}/\psi}$	0.11	0.36	0.38	0.13	1.0
$\sigma_{\text{tot}}^{\text{3J}/\psi}$ (fb)	15	34	110	114	272
$N_{\text{tot}}^{\text{3J}/\psi}$	0.3	0.6	2.0	2.1	5.0

three nonprompt J/ ψ mesons is $\approx 45\%$. The remaining half of the triple-J/ ψ events are expected to be due to the combination of J/ ψ mesons produced promptly and from beauty hadron decays. This result is consistent, within the large statistical uncertainties of the present data set, with the combination of prompt and nonprompt J/ ψ mesons derived from the decay length of each dimuon candidate.

In Fig. 3, the $\sigma_{\text{eff},\text{DPS}}$ value extracted here (red circle) is compared to the world data on effective DPS cross sections derived from midrapidity measurements with quarkonium final states [22, 24–26, 50] (blue circles), as well as from processes with jets, photons, and/or W bosons [13–19, 51–56] (black squares and triangles). A few of the $\sigma_{\text{eff},\text{DPS}}$ values plotted have been derived by more advanced phenomenological studies [57–60] of the experimental quarkonium data. The effective cross sections obtained from quarkonium measurements favor a smaller value of $\sigma_{\text{eff},\text{DPS}} \approx 3\text{--}10 \text{ mb}$ compared to the $\sigma_{\text{eff},\text{DPS}} \approx 10\text{--}20 \text{ mb}$ derived from harder or heavier final states. Such an apparent process-dependent $\sigma_{\text{eff},\text{DPS}}$ value is suggestive of different parton transverse profiles, and/or correlations present, probed inside the proton at varying fractional momenta, given by $x = \sqrt{p_{T,V}^2 + m_V^2 e^\eta} / \sqrt{s}$, for $V = \text{J}/\psi, \text{Y}, \text{W}, \text{Z}$. At midrapidity ($|\eta| < 2.5$), quarkonia are produced mostly in gluon-gluon scatterings carrying a fraction $x \approx 5 \times 10^{-4}$ of the proton momentum, whereas mostly quarks with $x \approx 10^{-2}$ participate in the production of EW bosons. The fact that LHCb measurements of double-quarkonia and quarkonia-plus-charm [25, 61] at *forward* rapidities ($\eta \approx 2\text{--}4.5$), processes that originate in parton scatterings with asymmetric fractional momenta $x_1 \approx 10^{-4}$ and $x_2 \approx 10^{-2}$, lead to values of $\sigma_{\text{eff},\text{DPS}} \approx 15 \text{ mb}$, larger than those measured at midrapidity for similar final states, seems to confirm the dependence of the effective DPS cross section on the relevant parton species and x fractions probed.

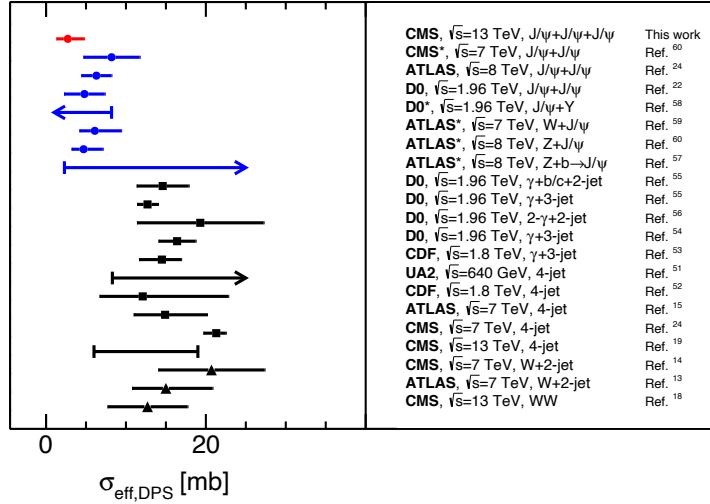


Figure 3: Comparison of $\sigma_{\text{eff},\text{DPS}}$ parameters extracted in various processes. The result obtained here (upper red circle) is compared to those derived in midrapidity measurements of double-quarkonium and EW boson plus quarkonium production [22, 24, 25, 57–60] (blue circles), as well as in final states with jets [19, 51, 52, 62], γ + jets [53–56], W + jets [13, 14], and same-sign W bosons [18] (black squares and triangles). The arrows indicate lower (or upper) limits at 95% (68%) confidence level. For the experimental results marked with a star, more recent theoretical reinterpretations based on more accurate calculations of the corresponding SPS cross section are plotted. The original experimental results can be found in Ref. [23] (CMS), Ref. [26] (D0) and Refs. [50, 63] (ATLAS).

References

- [1] Axial Field Spectrometer Collaboration, “Double parton scattering in pp collisions at $\sqrt{s} = 63$ GeV”, *Z. Phys. C* **34** (1987) 163, doi:10.1007/BF01566757.
- [2] T. Sjöstrand and M. van Zijl, “A multiple interaction model for the event structure in hadron collisions”, *Phys. Rev. D* **36** (1987) 2019, doi:10.1103/PhysRevD.36.2019.
- [3] P. Bartalini and J. R. Gaunt, eds., “Multiple parton interactions at the LHC”, volume 29. World Scientific, 2019. doi:10.1142/10646, ISBN 978-981-322-775-0, 978-981-322-777-4.
- [4] D. d’Enterria and A. M. Snigirev, “Triple parton scatterings in high-energy proton-proton collisions”, *Phys. Rev. Lett.* **118** (2017) 122001, doi:10.1103/PhysRevLett.118.122001, arXiv:1612.05582.
- [5] M. Diehl, D. Ostermeier, and A. Schafer, “Elements of a theory for multiparton interactions in QCD”, *JHEP* **03** (2012) 089, doi:10.1007/JHEP03(2012)089, arXiv:1111.0910. [Erratum: doi:10.1007/JHEP03(2016)001].
- [6] B. Blok, Y. Dokshitser, L. Frankfurt, and M. Strikman, “pQCD physics of multiparton interactions”, *Eur. Phys. J. C* **72** (2012) 1963, doi:10.1140/epjc/s10052-012-1963-8, arXiv:1106.5533.
- [7] CMS Collaboration, “Search for Higgs and Z boson decays to J/ψ or Y pairs in the four-muon final state in proton-proton collisions at $\sqrt{s} = 13$ TeV”, *Phys. Lett. B* **797** (2019) 134811, doi:10.1016/j.physletb.2019.134811, arXiv:1905.10408.

- [8] CMS Collaboration, “Measurement of the $\Upsilon(1S)$ pair production cross section and search for resonances decaying to $\Upsilon(1S)\mu^+\mu^-$ in proton-proton collisions at $\sqrt{s} = 13$ TeV”, *Phys. Lett. B* **808** (2020) 135578, doi:10.1016/j.physletb.2020.135578, arXiv:2002.06393.
- [9] D. d’Enterria and A. M. Snigirev, “Double, triple, and n -parton scatterings in high-energy proton and nuclear collisions”, *Adv. Ser. Direct. High Energy Phys.* **29** (2018) 159, doi:10.1142/9789813227767_0009, arXiv:1708.07519.
- [10] E. Chapon et al., “Perspectives for quarkonium studies at the high-luminosity LHC”, *Prog. Part. Nucl. Phys.* **121** (2021) 103906, doi:10.1016/j.ppnp.2021.103906, arXiv:2012.14161.
- [11] T. Sjöstrand et al., “An introduction to PYTHIA 8.2”, *Comput. Phys. Commun.* **191** (2015) 159, doi:10.1016/j.cpc.2015.01.024, arXiv:1410.3012.
- [12] M. H. Seymour and A. Siomok, “Constraining MPI models using σ_{eff} and recent Tevatron and LHC underlying event data”, *JHEP* **10** (2013) 113, doi:10.1007/JHEP10(2013)113, arXiv:1307.5015.
- [13] ATLAS Collaboration, “Measurement of hard double-parton interactions in $W(\rightarrow l\nu) + 2$ jet events at $\sqrt{s} = 7$ TeV with the ATLAS detector”, *New J. Phys.* **15** (2013) 033038, doi:10.1088/1367-2630/15/3/033038, arXiv:1301.6872.
- [14] CMS Collaboration, “Study of double parton scattering using $W + 2$ -jet events in proton-proton collisions at $\sqrt{s} = 7$ TeV”, *JHEP* **03** (2014) 032, doi:10.1007/JHEP03(2014)032, arXiv:1312.5729.
- [15] ATLAS Collaboration, “Study of hard double-parton scattering in four-jet events in pp collisions at $\sqrt{s} = 7$ TeV with the ATLAS experiment”, *JHEP* **11** (2016) 110, doi:10.1007/JHEP11(2016)110, arXiv:1608.01857.
- [16] CMS Collaboration, “Constraints on the double-parton scattering cross section from same-sign W boson pair production in proton-proton collisions at $\sqrt{s} = 8$ TeV”, *JHEP* **02** (2018) 032, doi:10.1007/JHEP02(2018)032, arXiv:1712.02280.
- [17] ATLAS Collaboration, “Study of the hard double-parton scattering contribution to inclusive four-lepton production in pp collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector”, *Phys. Lett. B* **790** (2019) 595, doi:10.1016/j.physletb.2019.01.062, arXiv:1811.11094.
- [18] CMS Collaboration, “Evidence for WW production from double-parton interactions in proton-proton collisions at $\sqrt{s} = 13$ TeV”, *Eur. Phys. J. C* **80** (2020) 41, doi:10.1140/epjc/s10052-019-7541-6, arXiv:1909.06265.
- [19] CMS Collaboration, “Measurement of double-parton scattering in inclusive production of four jets with low transverse momentum in proton-proton collisions at $\sqrt{s} = 13$ TeV”, *JHEP* **01** (2022) 177, doi:10.1007/JHEP01(2022)177, arXiv:2109.13822.
- [20] B. Blok and M. Strikman, “Multiparton pp and pA collisions: from geometry to parton–parton correlations”, *Adv. Ser. Direct. High Energy Phys.* **29** (2018) 63, doi:10.1142/9789813227767_0005, arXiv:1709.00334.

- [21] LHCb Collaboration, “Observation of J/ψ pair production in pp collisions at $\sqrt{s} = 7$ TeV”, *Phys. Lett. B* **707** (2012) 52, doi:10.1016/j.physletb.2011.12.015, arXiv:1109.0963.
- [22] D0 Collaboration, “Observation and studies of double J/ψ production at the Tevatron”, *Phys. Rev. D* **90** (2014) 111101, doi:10.1103/PhysRevD.90.111101, arXiv:1406.2380.
- [23] CMS Collaboration, “Measurement of prompt J/ψ pair production in pp collisions at $\sqrt{s} = 7$ TeV”, *JHEP* **09** (2014) 094, doi:10.1007/JHEP09(2014)094, arXiv:1406.0484.
- [24] ATLAS Collaboration, “Measurement of the prompt J/ψ pair production cross-section in pp collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector”, *Eur. Phys. J. C* **77** (2017) 76, doi:10.1140/epjc/s10052-017-4644-9, arXiv:1612.02950.
- [25] LHCb Collaboration, “Measurement of the J/ψ pair production cross-section in pp collisions at $\sqrt{s} = 13$ TeV”, *JHEP* **06** (2017) 047, doi:10.1007/JHEP06(2017)047, arXiv:1612.07451. [Erratum: doi:10.1007/JHEP10(2017)068].
- [26] D0 Collaboration, “Evidence for simultaneous production of J/ψ and Y mesons”, *Phys. Rev. Lett.* **116** (2016) 082002, doi:10.1103/PhysRevLett.116.082002, arXiv:1511.02428.
- [27] CMS Collaboration, “Observation of $Y(1S)$ pair production in proton-proton collisions at $\sqrt{s} = 8$ TeV”, *JHEP* **05** (2017) 013, doi:10.1007/JHEP05(2017)013, arXiv:1610.07095.
- [28] H.-S. Shao and Y.-J. Zhang, “Triple prompt J/ψ hadroproduction as a hard probe of multiple-parton scatterings”, *Phys. Rev. Lett.* **122** (2019) 192002, doi:10.1103/PhysRevLett.122.192002, arXiv:1902.04949.
- [29] H.-S. Shao, “HELAC-Onia: An automatic matrix element generator for heavy quarkonium physics”, *Comput. Phys. Commun.* **184** (2013) 2562, doi:10.1016/j.cpc.2013.05.023, arXiv:1212.5293.
- [30] H.-S. Shao, “HELAC-Onia 2.0: an upgraded matrix-element and event generator for heavy quarkonium physics”, *Comput. Phys. Commun.* **198** (2016) 238, doi:10.1016/j.cpc.2015.09.011, arXiv:1507.03435.
- [31] Particle Data Group Collaboration, “Review of particle physics”, *PTEP* **2020** (2020) 083C01, doi:10.1093/ptep/ptaa104.
- [32] CMS Collaboration, “Prompt and non-prompt J/ψ production in pp collisions at $\sqrt{s} = 7$ TeV”, *Eur. Phys. J. C* **71** (2011) 1575, doi:10.1140/epjc/s10052-011-1575-8, arXiv:1011.4193.
- [33] CMS Collaboration, “ J/ψ and $\psi(2S)$ production in pp collisions at $\sqrt{s} = 7$ TeV”, *JHEP* **02** (2012) 011, doi:10.1007/JHEP02(2012)011, arXiv:1111.1557.
- [34] CMS Collaboration, “Measurement of J/ψ and $\psi(2S)$ prompt double-differential cross sections in pp collisions at $\sqrt{s} = 7$ TeV”, *Phys. Rev. Lett.* **114** (2015) 191802, doi:10.1103/PhysRevLett.114.191802, arXiv:1502.04155.

- [35] CMS Collaboration, “Measurement of prompt and nonprompt J/ψ production in pp and pPb collisions at $\sqrt{s_{\text{NN}}} = 5.02 \text{ TeV}$ ”, *Eur. Phys. J. C* **77** (2017) 269, doi:10.1140/epjc/s10052-017-4828-3, arXiv:1702.01462.
- [36] G. Cowan, K. Cranmer, E. Gross, and O. Vitells, “Asymptotic formulae for likelihood-based tests of new physics”, *Eur. Phys. J. C* **71** (2011) 1554, doi:10.1140/epjc/s10052-011-1554-0, arXiv:1007.1727. [Erratum: doi:10.1140/epjc/s10052-013-2501-z].
- [37] S. S. Wilks, “The large-sample distribution of the likelihood ratio for testing composite hypotheses”, *Annals Math. Statist.* **9** (1938) 60, doi:10.1214/aoms/1177732360.
- [38] M. Pivk and F. R. Le Diberder, “sPlot: A statistical tool to unfold data distributions”, *Nucl. Instrum. Meth. A* **555** (2005) 356, doi:10.1016/j.nima.2005.08.106, arXiv:physics/0402083.
- [39] CMS Collaboration, “Performance of the CMS muon detector and muon reconstruction with proton-proton collisions at $\sqrt{s} = 13 \text{ TeV}$ ”, *JINST* **13** (2018) P06015, doi:10.1088/1748-0221/13/06/P06015, arXiv:1804.04528.
- [40] M. J. Oreglia, “A study of the reactions $\psi' \rightarrow \gamma\gamma\psi$ ”. PhD thesis, Stanford University, 1980. SLAC Report SLAC-R-236.
- [41] CMS Collaboration, “Precision luminosity measurement in proton-proton collisions at $\sqrt{s} = 13 \text{ TeV}$ in 2015 and 2016 at CMS”, *Eur. Phys. J. C* **81** (2021) 800, doi:10.1140/epjc/s10052-021-09538-2, arXiv:2104.01927.
- [42] CMS Collaboration, “CMS luminosity measurement for the 2017 data-taking period at $\sqrt{s} = 13 \text{ TeV}$ ”, CMS Physics Analysis Summary CMS-PAS-LUM-17-004, 2017.
- [43] CMS Collaboration, “CMS luminosity measurement for the 2018 data-taking period at $\sqrt{s} = 13 \text{ TeV}$ ”, CMS Physics Analysis Summary CMS-PAS-LUM-18-002, 2019.
- [44] J.-P. Lansberg and H.-S. Shao, “Production of $J/\psi + \eta_c$ versus $J/\psi + J/\psi$ at the LHC: Importance of real α_s^5 corrections”, *Phys. Rev. Lett.* **111** (2013) 122001, doi:10.1103/PhysRevLett.111.122001, arXiv:1308.0474.
- [45] J.-P. Lansberg and H.-S. Shao, “ J/ψ -pair production at large momenta: Indications for double parton scatterings and large α_s^5 contributions”, *Phys. Lett. B* **751** (2015) 479, doi:10.1016/j.physletb.2015.10.083, arXiv:1410.8822.
- [46] J.-P. Lansberg and H.-S. Shao, “Towards an automated tool to evaluate the impact of the nuclear modification of the gluon density on quarkonium, D and B meson production in proton–nucleus collisions”, *Eur. Phys. J. C* **77** (2017) 1, doi:10.1140/epjc/s10052-016-4575-x, arXiv:1610.05382.
- [47] ATLAS Collaboration, “Measurement of the differential cross-sections of prompt and non-prompt production of J/ψ and $\psi(2S)$ in pp collisions at $\sqrt{s} = 7$ and 8 TeV with the ATLAS detector”, *Eur. Phys. J. C* **76** (2016) 283, doi:10.1140/epjc/s10052-016-4050-8, arXiv:1512.03657.
- [48] J. Alwall et al., “The automated computation of tree-level and next-to-leading order differential cross sections, and their matching to parton shower simulations”, *JHEP* **07** (2014) 079, doi:10.1007/JHEP07(2014)079, arXiv:1405.0301.

- [49] S. Dulat et al., “New parton distribution functions from a global analysis of quantum chromodynamics”, *Phys. Rev. D* **93** (2016) 033006,
`doi:10.1103/PhysRevD.93.033006`, `arXiv:1506.07443`.
- [50] ATLAS Collaboration, “Observation and measurements of the production of prompt and non-prompt J/ψ mesons in association with a Z boson in pp collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector”, *Eur. Phys. J. C* **75** (2015) 229,
`doi:10.1140/epjc/s10052-015-3406-9`, `arXiv:1412.6428`.
- [51] UA2 Collaboration, “A study of multi-jet events at the CERN $\bar{p}p$ collider and a search for double parton scattering”, *Phys. Lett. B* **268** (1991) 145,
`doi:10.1016/0370-2693(91)90937-L`.
- [52] CDF Collaboration, “Study of four jet events and evidence for double parton interactions in $\bar{p}p$ collisions at $\sqrt{s} = 1.8$ TeV”, *Phys. Rev. D* **47** (1993) 4857,
`doi:10.1103/PhysRevD.47.4857`.
- [53] CDF Collaboration, “Double parton scattering in $\bar{p}p$ collisions at $\sqrt{s} = 1.8$ TeV”, *Phys. Rev. D* **56** (1997) 3811, `doi:10.1103/PhysRevD.56.3811`.
- [54] D0 Collaboration, “Double parton interactions in $\gamma+3$ jet events in $\bar{p}p$ collisions $\sqrt{s} = 1.96$ TeV”, *Phys. Rev. D* **81** (2010) 052012, `doi:10.1103/PhysRevD.81.052012`,
`arXiv:0912.5104`.
- [55] D0 Collaboration, “Double parton interactions in $\gamma+3$ jet and $\gamma+b/c$ jet+2 jet events in $\bar{p}p$ collisions at $\sqrt{s} = 1.96$ TeV”, *Phys. Rev. D* **89** (2014) 072006,
`doi:10.1103/PhysRevD.89.072006`, `arXiv:1402.1550`.
- [56] D0 Collaboration, “Study of double parton interactions in diphoton + dijet events in $\bar{p}p$ collisions at $\sqrt{s} = 1.96$ TeV”, *Phys. Rev. D* **93** (2016) 052008,
`doi:10.1103/PhysRevD.93.052008`, `arXiv:1512.05291`.
- [57] J.-P. Lansberg and H.-S. Shao, “Phenomenological analysis of associated production of $Z^0 + b$ in the $b \rightarrow J/\psi X$ decay channel at the LHC”, *Nucl. Phys. B* **916** (2017) 132,
`doi:10.1016/j.nuclphysb.2017.01.002`, `arXiv:1611.09303`.
- [58] H.-S. Shao and Y.-J. Zhang, “Complete study of hadroproduction of a Y meson associated with a prompt J/ψ ”, *Phys. Rev. Lett.* **117** (2016) 062001,
`doi:10.1103/PhysRevLett.117.062001`, `arXiv:1605.03061`.
- [59] J.-P. Lansberg, H.-S. Shao, and N. Yamanaka, “Indication for double parton scatterings in $W +$ prompt J/ψ production at the LHC”, *Phys. Lett. B* **781** (2018) 485,
`doi:10.1016/j.physletb.2018.04.020`, `arXiv:1707.04350`.
- [60] J.-P. Lansberg, “New observables in inclusive production of quarkonia”, *Phys. Rept.* **889** (2020) 1, `doi:10.1016/j.physrep.2020.08.007`, `arXiv:1903.09185`.
- [61] LHCb Collaboration, “Observation of double charm production involving open charm in pp collisions at $\sqrt{s} = 7$ TeV”, *JHEP* **06** (2012) 141, `doi:10.1007/JHEP06(2012)141`,
`arXiv:1205.0975`. [Addendum: `doi:10.1007/JHEP03(2014)108`].
- [62] CMS Collaboration, “Event generator tunes obtained from underlying event and multiparton scattering measurements”, *Eur. Phys. J. C* **76** (2016) 155,
`doi:10.1140/epjc/s10052-016-3988-x`, `arXiv:1512.00815`.

- [63] ATLAS Collaboration, “Measurement of the production cross section of prompt J/ψ mesons in association with a W^\pm boson in pp collisions at $\sqrt{s} = 7\text{ TeV}$ with the ATLAS detector”, *JHEP* **04** (2014) 172, doi:10.1007/JHEP04(2014)172, arXiv:1401.2831.
- [64] CMS Collaboration, “The CMS experiment at the CERN LHC”, *JINST* **3** (2008) S08004, doi:10.1088/1748-0221/3/08/S08004.
- [65] CMS Collaboration, “Performance of the CMS Level-1 trigger in proton-proton collisions at $\sqrt{s} = 13\text{ TeV}$ ”, *JINST* **15** (2020) P10017, doi:10.1088/1748-0221/15/10/P10017, arXiv:2006.10165.
- [66] CMS Collaboration, “The CMS trigger system”, *JINST* **12** (2017) P01020, doi:10.1088/1748-0221/12/01/P01020, arXiv:1609.02366.
- [67] R. Frühwirth, “Application of Kalman filtering to track and vertex fitting”, *Nucl. Instrum. Meth. A* **262** (1987) 444, doi:10.1016/0168-9002(87)90887-4.
- [68] NNPDF Collaboration, “Parton distributions for the LHC Run II”, *JHEP* **04** (2015) 040, doi:10.1007/JHEP04(2015)040, arXiv:1410.8849.
- [69] GEANT4 Collaboration, “GEANT4—a simulation toolkit”, *Nucl. Instrum. Meth. A* **506** (2003) 250, doi:10.1016/S0168-9002(03)01368-8.
- [70] CMS Collaboration, “Particle-flow reconstruction and global event description with the CMS detector”, *JINST* **12** (2017) P10003, doi:10.1088/1748-0221/12/10/P10003, arXiv:1706.04965.
- [71] HEPData record for this analysis, 2021. doi:10.17182/hepdata.114984.

Methods

Experimental setup

The central feature of the CMS apparatus is a superconducting solenoid of 6 m internal diameter, providing a magnetic field of 3.8 T. Within the solenoid volume are a silicon pixel and strip tracker, a lead tungstate crystal electromagnetic calorimeter, and a brass and scintillator hadron calorimeter, each composed of a barrel and two endcap sections. Forward calorimeters extend the η coverage provided by the barrel and endcap detectors. Muons are measured over the range $|\eta| < 2.4$ in gas-ionization detectors, embedded in the steel flux-return yoke outside the solenoid, made using three technologies: drift tubes, cathode strip chambers, and resistive plate chambers. A more detailed description of the CMS detector can be found in Ref. [64].

Events of interest are selected using a two-tiered trigger system. The first trigger level, composed of custom hardware processors, uses information from the calorimeters and muon detectors to select events at a rate of around 100 kHz with a fixed latency of about $4\mu\text{s}$ [65]. The second level (or high-level trigger, HLT) consists of a farm of processors running a version of the full event reconstruction software optimized for fast processing, and reduces the event rate to around 1 kHz before data storage [66]. The present analysis employs an HLT that requires three muons, each having $p_T > 3.5\text{ GeV}$ for $|\eta| < 1.2$ (barrel) or $p_T > 2.5\text{ GeV}$ for $1.2 < |\eta| < 2.4$ (endcap). In addition, the event must have at least one pair of oppositely charged muons with invariant mass between 2.80 and 3.35 GeV that originate from a common vertex with a probability greater than 0.5%, as determined by a Kalman vertex fit [67], thus suppressing random

combinations of muons from unrelated sources. Monte Carlo (MC) simulations are used to determine the trigger efficiency. Simulated events are generated using HELAC-ONIA (v.2.6.6) with the NNPDF3.0 PDF set [68], and PYTHIA 8.205 for the hadronization and decay with the CUETP8M1 underlying event tune [62]. Triple-J/ ψ events are simulated by combining events from two different MC samples with varying relative fractions. The first MC sample contains three singly produced J/ ψ mesons, whereas the second sample combines single- and double-J/ ψ meson production, following Ref. [28]. Since the J/ ψ mesons originating in both processes have slightly different p_T spectra, the variation of their relative fractions in the simulation allows to effectively scan the triple-muon trigger efficiency in the more uncertain region close to the trigger p_T thresholds. The generated events are then processed through a detailed GEANT4 simulation [69] of the CMS detector response.

Event reconstruction and selection

Muons are reconstructed by combining information from the silicon tracker and the muon system [39]. The matching between tracks reconstructed in each of the subsystems proceeds either outside-in, starting from a track in the muon system, or inside-out, starting from a track provided by the silicon tracker. Matching muons to tracks measured in the silicon tracker leads to a relative p_T resolution of 1% in the barrel and 3% in the endcaps for muons with p_T up to 100 GeV [39]. The candidate vertex with the largest value of summed physics-object p_T^2 in the event is taken to be the primary pp interaction vertex (PV) [70]. Only charged particles that are either directly participating in the PV determination, or are closest to the PV along the z direction and not used in any other PV identification (namely, they are consistent with secondary decays from the closest PV), are used in the analysis. Simulation studies show that this procedure efficiently suppresses any potential contamination from charged particles produced in any other pp collision taking place in the same bunch crossing (pileup).

The offline data analysis starts by selecting events with six or more reconstructed muons, each passing the p_T and η criteria implemented at the HLT. The muons are combined into OS pairs, and are considered for further study if their invariant mass is $2.9 < m_{\mu^+\mu^-} < 3.3$ GeV (corresponding to about ± 7 times the J/ ψ mass resolution discussed below) and originate from a common vertex with a probability greater than 0.5%, thereby reducing the random pairing of muons originating from other background sources in the same event, as discussed below. All selected muon pairs are further required to share the same PV (including the possibility that they originate from secondary vertices associated to a common PV) to eliminate accidental combinations of muons from different pp collisions in the same or neighboring bunch crossings. The analysis thereby includes prompt-J/ ψ mesons coming directly from the pp interaction (or from feed-down decays of promptly produced and decayed resonances), and nonprompt ones coming from the decays of beauty hadrons. In order to ensure high purity and reconstruction efficiency, the J/ ψ candidates are required to have $p_T > 6$ GeV and $|y| < 2.4$.

After applying the selection criteria discussed above, six triple-J/ ψ events are observed. No alternative pairings among the OS muons in these six events are found to satisfy the analysis requirements. In all events, the J/ ψ meson with highest p_T (“leading” J/ ψ) is found to correspond to the muon pair that passed the online trigger selection. In inclusive J/ ψ measurements [23, 32–35], a continuum background is present in the $m_{\mu^+\mu^-}$ distribution due to random combinations of OS muons originating from semileptonic beauty- and charm-quark hadron decays, $b \rightarrow \mu + X$ and $c \rightarrow \mu + X$, and Drell–Yan events, which pass the trigger and data analysis criteria. To monitor the sideband background population, the mass windows corresponding to the two subleading J/ ψ mesons are extended well below the J/ ψ mass region. The corresponding dimuon invariant mass distributions are shown in Fig. 2 ordered (left to

right) by decreasing p_T of the $\mu^+\mu^-$ system. Only one additional background event is found in the extended mass region indicated by the dotted curves, confirming that the combinatorial continuum is suppressed by the requirement of having three reconstructed J/ψ candidates in the same event.

Event kinematic properties

Detailed information of the kinematic properties of the J/ψ candidates passing the triple- J/ψ selection criteria are shown in Extended Data Table 4. The kinematic distributions of all six J/ψ triplets do not show any local peak, which could be indicative of, e.g., a resonance decaying into three J/ψ mesons, but are distributed featureless (with large point-to-point statistical uncertainties) over triple- J/ψ mass, p_T , and η .

All sources of systematic uncertainty in the triple- J/ψ cross section measurement are listed in Extended Data Table 5.

Table 4: Dimuon invariant mass, proper decay-length, transverse momentum, rapidity, and azimuthal angle of each of the three J/ψ candidates measured in the six triple- J/ψ events passing our selection criteria. (The last J/ψ candidate in the last row, with invariant mass $m^{J/\psi,3} = 2.94 \text{ GeV}$, is likely a background event).

Event	$m^{J/\psi,1}$ (GeV)	$m^{J/\psi,2}$ (GeV)	$m^{J/\psi,3}$ (GeV)	$L^{J/\psi,1}$ (mm)	$L^{J/\psi,2}$ (mm)	$L^{J/\psi,3}$ (mm)
1	3.08	3.10	3.07	1.77	0.24	-0.01
2	3.15	3.06	3.09	0.05	0.36	0.02
3	3.10	3.14	3.11	-0.04	0.03	0.05
4	3.07	3.03	3.09	0.48	0.81	0.82
5	3.12	3.14	3.14	-0.25	0.13	-0.02
6	3.06	3.17	2.94	0.11	0.38	0.61

Event	$p_T^{J/\psi,1}$ (GeV)	$p_T^{J/\psi,2}$ (GeV)	$p_T^{J/\psi,3}$ (GeV)	$y^{J/\psi,1}$	$y^{J/\psi,2}$	$y^{J/\psi,3}$
1	17.64	17.50	8.68	-2.25	-0.39	1.53
2	91.50	54.04	11.81	1.99	0.81	-0.71
3	11.29	10.29	6.98	-0.50	-0.37	-1.64
4	15.46	10.61	7.84	-0.83	-2.24	-1.78
5	8.67	7.71	6.75	2.03	-1.14	-1.87
6	60.70	19.09	17.03	1.59	2.29	1.58

Event	$\phi^{J/\psi,1}$	$\phi^{J/\psi,2}$	$\phi^{J/\psi,3}$
1	-1.98	2.06	-1.56
2	2.60	-2.14	-0.38
3	-0.87	-1.50	0.66
4	1.00	-2.07	-1.77
5	-1.77	1.99	2.91
6	-1.98	-1.74	-2.17

All sources of systematic uncertainty in the triple- J/ψ cross section measurement are listed in Extended Data Table 5.

Table 5: Relative contributions to the systematic uncertainty of the $\sigma(pp \rightarrow J/\psi J/\psi J/\psi X)$ measurement. The last row gives the sum in quadrature of all components.

Source	Relative uncertainty
J/ ψ meson signal shape	0.8%
Dimuon continuum background shape	3.4%
Muon reconstruction and identification	1.0%
Trigger efficiency	3.4%
MC sample size	3.0%
Integrated luminosity	1.6%
Dimuon branching fraction	1.7%
Total	6.2%

Data availability

Tabulated results are provided in the HEPData record for this analysis [71]. Release and preservation of data used by the CMS Collaboration as the basis for publications is guided by the CMS policy as stated in CMS data preservation, re-use and open access policy.

Code availability

The CMS core software is publically available at <https://github.com/cms-sw/cmssw>.

Acknowledgments

We congratulate our colleagues in the CERN accelerator departments for the excellent performance of the LHC and thank the technical and administrative staffs at CERN and at other CMS institutes for their contributions to the success of the CMS effort. In addition, we gratefully acknowledge the computing centers and personnel of the Worldwide LHC Computing Grid and other centers for delivering so effectively the computing infrastructure essential to our analyses. Finally, we acknowledge the enduring support for the construction and operation of the LHC, the CMS detector, and the supporting computing infrastructure provided by the following funding agencies: BMBWF and FWF (Austria); FNRS and FWO (Belgium); CNPq, CAPES, FAPERJ, FAPERGS, and FAPESP (Brazil); MES and BNSF (Bulgaria); CERN; CAS, MoST, and NSFC (China); MINCIENCIAS (Colombia); MSES and CSF (Croatia); RIF (Cyprus); SENESCYT (Ecuador); MoER, ERC PUT and ERDF (Estonia); Academy of Finland, MEC, and HIP (Finland); CEA and CNRS/IN2P3 (France); BMBF, DFG, and HGF (Germany); GSRI (Greece); NKFI (Hungary); DAE and DST (India); IPM (Iran); SFI (Ireland); INFN (Italy); MSIP and NRF (Republic of Korea); MES (Latvia); LAS (Lithuania); MOE and UM (Malaysia); BUAP, CINVESTAV, CONACYT, LNS, SEP, and UASLP-FAI (Mexico); MOS (Montenegro); MBIE (New Zealand); PAEC (Pakistan); MSHE and NSC (Poland); FCT (Portugal); JINR (Dubna); MON, RosAtom, RAS, RFBR, and NRC KI (Russia); MESTD (Serbia); SEIDI, CPAN, PCTI, and FEDER (Spain); MOSTR (Sri Lanka); Swiss Funding Agencies (Switzerland); MST (Taipei); ThEPCenter, IPST, STAR, and NSTDA (Thailand); TUBITAK and TAEK (Turkey); NASU (Ukraine); STFC (United Kingdom); DOE and NSF (USA).

A The CMS Collaboration

Yerevan Physics Institute, Yerevan, Armenia

A. Tumasyan

Institut für Hochenergiephysik, Vienna, Austria

W. Adam , J.W. Andrejkovic, T. Bergauer , S. Chatterjee , K. Damanakis, M. Dragicevic , A. Escalante Del Valle , R. Frühwirth¹, M. Jeitler¹ , N. Krammer, L. Lechner , D. Liko, I. Mikulec, P. Paulitsch, F.M. Pitters, J. Schieck¹ , R. Schöfbeck , D. Schwarz, S. Templ , W. Waltenberger , C.-E. Wulz¹

Institute for Nuclear Problems, Minsk, Belarus

V. Chekhovsky, A. Litomin, V. Makarenko 

Universiteit Antwerpen, Antwerpen, Belgium

M.R. Darwish², E.A. De Wolf, T. Janssen , T. Kello³, A. Lelek , H. Rejeb Sfar, P. Van Mechelen , S. Van Putte, N. Van Remortel 

Vrije Universiteit Brussel, Brussel, Belgium

F. Blekman , E.S. Bols , J. D'Hondt , M. Delcourt, H. El Faham , S. Lowette , S. Moortgat , A. Morton , D. Müller , A.R. Sahasransu , S. Tavernier , W. Van Doninck

Université Libre de Bruxelles, Bruxelles, Belgium

D. Beghin, B. Bilin , B. Clerbaux , G. De Lentdecker, L. Favart , A.K. Kalsi , K. Lee, M. Mahdavikhorrami, I. Makarenko , L. Moureaux , L. Pétré, A. Popov , N. Postiau, E. Starling , L. Thomas , M. Vanden Bemden, C. Vander Velde , P. Vanlaer 

Ghent University, Ghent, Belgium

T. Cornelis , D. Dobur, J. Knolle , L. Lambrecht, G. Mestdach, M. Niedziela , C. Rendón, C. Roskas, A. Samalan, K. Skovpen , M. Tytgat , B. Vermassen, L. Wezenbeek

Université Catholique de Louvain, Louvain-la-Neuve, Belgium

A. Benecke, A. Bethani , G. Bruno, F. Bury , C. Caputo , P. David , C. Delaere , I.S. Donertas , A. Giammanco , K. Jaffel, Sa. Jain , V. Lemaitre, K. Mondal , J. Prisciandaro, A. Taliercio, M. Teklishyn , T.T. Tran, P. Vischia , S. Wertz

Centro Brasileiro de Pesquisas Fisicas, Rio de Janeiro, Brazil

G.A. Alves , C. Hensel, A. Moraes , P. Rebello Teles 

Universidade do Estado do Rio de Janeiro, Rio de Janeiro, Brazil

W.L. Aldá Júnior , M. Alves Gallo Pereira , M. Barroso Ferreira Filho, H. Brandao Malbouisson, W. Carvalho , J. Chinellato⁴, E.M. Da Costa , G.G. Da Silveira⁵ , D. De Jesus Damiao , V. Dos Santos Sousa, S. Fonseca De Souza , C. Mora Herrera , K. Mota Amarilo, L. Mundim , H. Nogima, A. Santoro, S.M. Silva Do Amaral , A. Sznajder , M. Thiel, F. Torres Da Silva De Araujo⁶ , A. Vilela Pereira

Universidade Estadual Paulista (a), Universidade Federal do ABC (b), São Paulo, Brazil

C.A. Bernardes⁵ , L. Calligaris , T.R. Fernandez Perez Tomei , E.M. Gregores , D.S. Lemos , P.G. Mercadante , S.F. Novaes , Sandra S. Padula 

Institute for Nuclear Research and Nuclear Energy, Bulgarian Academy of Sciences, Sofia, Bulgaria

A. Aleksandrov, G. Antchev , R. Hadjiiska, P. Iaydjiev, M. Misheva, M. Rodozov, M. Shopova, G. Sultanov

University of Sofia, Sofia, Bulgaria

A. Dimitrov, T. Ivanov, L. Litov , B. Pavlov, P. Petkov, A. Petrov

Beihang University, Beijing, China

T. Cheng , T. Javaid⁷, M. Mittal, L. Yuan

Department of Physics, Tsinghua University, Beijing, China

M. Ahmad , G. Bauer, C. Dozen⁸ , Z. Hu , J. Martins⁹ , Y. Wang, K. Yi^{10,11}

Institute of High Energy Physics, Beijing, China

E. Chapon , G.M. Chen⁷ , H.S. Chen⁷ , M. Chen , F. Iemmi, A. Kapoor , D. Leggat, H. Liao, Z.-A. Liu⁷ , V. Milosevic , F. Monti , R. Sharma , J. Tao , J. Thomas-Wilsker, J. Wang , H. Zhang , J. Zhao 

State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing, China

A. Agapitos, Y. An, Y. Ban, C. Chen, A. Levin , Q. Li , X. Lyu, Y. Mao, S.J. Qian, D. Wang , J. Xiao

Sun Yat-Sen University, Guangzhou, China

M. Lu, Z. You 

Institute of Modern Physics and Key Laboratory of Nuclear Physics and Ion-beam Application (MOE) - Fudan University, Shanghai, China

X. Gao³, H. Okawa , Y. Zhang 

Zhejiang University, Hangzhou, China, Zhejiang, China

Z. Lin , M. Xiao 

Universidad de Los Andes, Bogota, Colombia

C. Avila , A. Cabrera , C. Florez , J. Fraga

Universidad de Antioquia, Medellin, Colombia

J. Mejia Guisao, F. Ramirez, J.D. Ruiz Alvarez , C.A. Salazar Gonzalez 

University of Split, Faculty of Electrical Engineering, Mechanical Engineering and Naval Architecture, Split, Croatia

D. Giljanovic, N. Godinovic , D. Lelas , I. Puljak 

University of Split, Faculty of Science, Split, Croatia

Z. Antunovic, M. Kovac, T. Sculac 

Institute Rudjer Boskovic, Zagreb, Croatia

V. Brigljevic , D. Ferencek , D. Majumder , M. Roguljic, A. Starodumov¹² , T. Susa 

University of Cyprus, Nicosia, Cyprus

A. Attikis , K. Christoforou, A. Ioannou, G. Kole , M. Kolosova, S. Konstantinou, J. Mousa , C. Nicolaou, F. Ptochos , P.A. Razis, H. Rykaczewski, H. Saka 

Charles University, Prague, Czech Republic

M. Finger¹³, M. Finger Jr.¹³ , A. Kveton

Escuela Politecnica Nacional, Quito, Ecuador

E. Ayala

Universidad San Francisco de Quito, Quito, Ecuador

E. Carrera Jarrin 

Academy of Scientific Research and Technology of the Arab Republic of Egypt, Egyptian Network of High Energy Physics, Cairo, Egypt

A.A. Abdelalim^{14,15} , S. Abu Zeid¹⁶ 

Center for High Energy Physics (CHEP-FU), Fayoum University, El-Fayoum, Egypt

M.A. Mahmoud , Y. Mohammed 

National Institute of Chemical Physics and Biophysics, Tallinn, Estonia

S. Bhowmik , R.K. Dewanjee , K. Ehataht, M. Kadastik, S. Nandan, C. Nielsen, J. Pata, M. Raidal , L. Tani, C. Veelken

Department of Physics, University of Helsinki, Helsinki, Finland

P. Eerola , H. Kirschenmann , K. Osterberg , M. Voutilainen 

Helsinki Institute of Physics, Helsinki, Finland

S. Bharthuar, E. Brücken , F. Garcia , J. Havukainen , M.S. Kim , R. Kinnunen, T. Lampén, K. Lassila-Perini , S. Lehti , T. Lindén, M. Lotti, L. Martikainen, M. Myllymäki, J. Ott , H. Siikonen, E. Tuominen , J. Tuominiemi

Lappeenranta University of Technology, Lappeenranta, Finland

P. Luukka , H. Petrow, T. Tuuva

IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France

C. Amendola , M. Besancon, F. Couderc , M. Dejardin, D. Denegri, J.L. Faure, F. Ferri , S. Ganjour, P. Gras, G. Hamel de Monchenault , P. Jarry, B. Lenzi , E. Locci, J. Malcles, J. Rander, A. Rosowsky , M.Ö. Sahin , A. Savoy-Navarro¹⁷, M. Titov , G.B. Yu 

Laboratoire Leprince-Ringuet, CNRS/IN2P3, Ecole Polytechnique, Institut Polytechnique de Paris, Palaiseau, France

S. Ahuja , F. Beaudette , M. Bonanomi , A. Buchot Perraguin, P. Busson, A. Cappati, C. Charlot, O. Davignon, B. Diab, G. Falmagne , S. Ghosh, R. Granier de Cassagnac , A. Hakimi, I. Kucher , J. Motta, M. Nguyen , C. Ochando , P. Paganini , J. Rembser, R. Salerno , U. Sarkar , J.B. Sauvan , Y. Sirois , A. Tarabini, A. Zabi, A. Zghiche 

Université de Strasbourg, CNRS, IPHC UMR 7178, Strasbourg, France

J.-L. Agram¹⁸ , J. Andrea, D. Apparu, D. Bloch , G. Bourgatte, J.-M. Brom, E.C. Chabert, C. Collard , D. Darej, J.-C. Fontaine¹⁸, U. Goerlach, C. Grimault, A.-C. Le Bihan, E. Nibigira , P. Van Hove 

Institut de Physique des 2 Infinis de Lyon (IP2I), Villeurbanne, France

E. Asilar , S. Beauceron , C. Bernet , G. Boudoul, C. Camen, A. Carle, N. Chanon , D. Contardo, P. Depasse , H. El Mamouni, J. Fay, S. Gascon , M. Gouzevitch , B. Ille, I.B. Laktineh, H. Lattaud , A. Lesauvage , M. Lethuillier , L. Mirabito, S. Perries, K. Shchablo, V. Sordini , L. Torterotot , G. Touquet, M. Vander Donckt, S. Viret

Georgian Technical University, Tbilisi, Georgia

I. Lomidze, T. Toriashvili¹⁹, Z. Tsamalaidze¹³

RWTH Aachen University, I. Physikalisches Institut, Aachen, Germany

V. Botta, L. Feld , K. Klein, M. Lipinski, D. Meuser, A. Pauls, N. Röwert, J. Schulz, M. Teroerde 

RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany

A. Dodonova, D. Eliseev, M. Erdmann , P. Fackeldey , B. Fischer, S. Ghosh , T. Hebbeker , K. Hoepfner, F. Ivone, L. Mastrolorenzo, M. Merschmeyer , A. Meyer , G. Mocellin, S. Mondal, S. Mukherjee , D. Noll , A. Novak, T. Pook , A. Pozdnyakov , Y. Rath, H. Reithler, J. Roemer, A. Schmidt , S.C. Schuler, A. Sharma , L. Vigilante,

S. Wiedenbeck, S. Zaleski

RWTH Aachen University, III. Physikalisches Institut B, Aachen, Germany

C. Dziwok, G. Flügge, W. Haj Ahmad²⁰ , O. Hlushchenko, T. Kress, A. Nowack , O. Pooth, D. Roy , A. Stahl²¹ , T. Ziemons , A. Zotz

Deutsches Elektronen-Synchrotron, Hamburg, Germany

H. Aarup Petersen, M. Aldaya Martin, P. Asmuss, S. Baxter, M. Bayatmakou, O. Behnke, A. Bermúdez Martínez, S. Bhattacharya, A.A. Bin Anuar , K. Borras²², D. Brunner, A. Campbell , A. Cardini , C. Cheng, F. Colombina, S. Consuegra Rodríguez , G. Correia Silva, V. Danilov, M. De Silva, L. Didukh, G. Eckerlin, D. Eckstein, L.I. Estevez Banos , O. Filatov , E. Gallo²³, A. Geiser, A. Giraldi, A. Grohsjean , M. Guthoff, A. Jafari²⁴ , N.Z. Jomhari , H. Jung , A. Kasem²² , M. Kasemann , H. Kaveh , C. Kleinwort , R. Kogler , D. Krücker , W. Lange, J. Lidrych , K. Lipka, W. Lohmann²⁵, R. Mankel, I.-A. Melzer-Pellmann , M. Mendizabal Morentin, J. Metwally, A.B. Meyer , M. Meyer , J. Mnich , A. Mussgiller, Y. Otarid, D. Pérez Adán , D. Pitzl, A. Raspereza, B. Ribeiro Lopes, J. Rübenach, A. Saggio , A. Saibel , M. Savitskyi , M. Scham²⁶, V. Scheurer, S. Schnake, P. Schütze, C. Schwanenberger²³ , M. Shchedrolosiev, R.E. Sosa Ricardo , D. Stafford, N. Tonon , M. Van De Klundert , R. Walsh , D. Walter, Q. Wang , Y. Wen , K. Wichmann, L. Wiens, C. Wissing, S. Wuchterl 

University of Hamburg, Hamburg, Germany

R. Aggleton, S. Albrecht , S. Bein , L. Benato , P. Connor , K. De Leo , M. Eich, F. Feindt, A. Fröhlich, C. Garbers , E. Garutti , P. Gunnellini, M. Hajheidari, J. Haller , A. Hinzmann , G. Kasieczka, R. Klanner , T. Kramer, V. Kutzner, J. Lange , T. Lange , A. Lobanov , A. Malara , A. Nigamova, K.J. Pena Rodriguez, M. Rieger , O. Rieger, P. Schleper, M. Schröder , J. Schwandt , J. Sonneveld , H. Stadie, G. Steinbrück, A. Tews, I. Zoi 

Karlsruher Institut fuer Technologie, Karlsruhe, Germany

J. Bechtel , S. Brommer, M. Burkart, E. Butz , R. Caspart , T. Chwalek, W. De Boer[†], A. Dierlamm, A. Droll, K. El Morabit, N. Faltermann , M. Giffels, J.O. Gosewisch, A. Gottmann, F. Hartmann²¹ , C. Heidecker, U. Husemann , P. Keicher, R. Koppenhöfer, S. Maier, M. Metzler, S. Mitra , Th. Müller, M. Neukum, A. Nürnberg, G. Quast , K. Rabbertz , J. Rauser, D. Savoiu , M. Schnepf, D. Seith, I. Shvetsov, H.J. Simonis, R. Ulrich , J. Van Der Linden, R.F. Von Cube, M. Wassmer, M. Weber , S. Wieland, R. Wolf , S. Wozniewski, S. Wunsch

Institute of Nuclear and Particle Physics (INPP), NCSR Demokritos, Aghia Paraskevi, Greece

G. Anagnostou, G. Daskalakis, T. Geralis , A. Kyriakis, D. Loukas, A. Stakia 

National and Kapodistrian University of Athens, Athens, Greece

M. Diamantopoulou, D. Karasavvas, P. Kontaxakis , C.K. Koraka, A. Manousakis-Katsikakis, A. Panagiotou, I. Papavergou, N. Saoulidou , K. Theofilatos , E. Tziaferi , K. Vellidis, E. Vourliotis

National Technical University of Athens, Athens, Greece

G. Bakas, K. Kousouris , I. Papakrivopoulos, G. Tsipolitis, A. Zacharopoulou

University of Ioánnina, Ioánnina, Greece

K. Adamidis, I. Bestintzanos, I. Evangelou , C. Foudas, P. Gianneios, P. Katsoulis, P. Kokkas, N. Manthos, I. Papadopoulos , J. Strologas 

MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary

M. Csanad , K. Farkas, M.M.A. Gadallah²⁷ , S. Lököс²⁸ , P. Major, K. Mandal , A. Mehta , G. Pasztor , A.J. Rádl, O. Surányi, G.I. Veres 

Wigner Research Centre for Physics, Budapest, Hungary

M. Bartók²⁹ , G. Bencze, C. Hajdu , D. Horvath³⁰ , F. Sikler , V. Veszpremi 

Institute of Nuclear Research ATOMKI, Debrecen, Hungary

S. Czellar, D. Fasanella , F. Fienga , J. Karancsi²⁹ , J. Molnar, Z. Szillasi, D. Teyssier

Institute of Physics, University of Debrecen, Debrecen, Hungary

P. Raics, Z.L. Trocsanyi³¹ , B. Ujvari

Karoly Robert Campus, MATE Institute of Technology, Gyongyos, Hungary

T. Csorgo³² , F. Nemes³², T. Novak

Indian Institute of Science (IISc), Bangalore, India

S. Choudhury, J.R. Komaragiri , D. Kumar, L. Panwar , P.C. Tiwari 

National Institute of Science Education and Research, HBNI, Bhubaneswar, India

S. Bahinipati³³ , C. Kar , P. Mal, T. Mishra , V.K. Muraleedharan Nair Bindhu³⁴, A. Nayak³⁴ , P. Saha, N. Sur , S.K. Swain, D. Vats³⁴

Panjab University, Chandigarh, India

S. Bansal , S.B. Beri, V. Bhatnagar , G. Chaudhary , S. Chauhan , N. Dhingra³⁵ , R. Gupta, A. Kaur, M. Kaur , P. Kumari , M. Meena, K. Sandeep , J.B. Singh , A.K. Virdi 

University of Delhi, Delhi, India

A. Ahmed, A. Bhardwaj , B.C. Choudhary , M. Gola, S. Keshri , A. Kumar , M. Naimuddin , P. Priyanka , K. Ranjan, A. Shah 

Saha Institute of Nuclear Physics, HBNI, Kolkata, India

M. Bharti³⁶, R. Bhattacharya, S. Bhattacharya , D. Bhowmik, S. Dutta, S. Dutta, B. Gomber³⁷ , M. Maity³⁸, P. Palit , P.K. Rout , G. Saha, B. Sahu , S. Sarkar, M. Sharan, S. Thakur³⁶

Indian Institute of Technology Madras, Madras, India

P.K. Behera , S.C. Behera, P. Kalbhor , A. Muhammad, R. Pradhan, P.R. Pujahari, A. Sharma , A.K. Sikdar

Bhabha Atomic Research Centre, Mumbai, India

D. Dutta , V. Jha, V. Kumar , D.K. Mishra, K. Naskar³⁹, P.K. Netrakanti, L.M. Pant, P. Shukla 

Tata Institute of Fundamental Research-A, Mumbai, India

T. Aziz, S. Dugad, M. Kumar

Tata Institute of Fundamental Research-B, Mumbai, India

S. Banerjee , R. Chudasama, M. Guchait, S. Karmakar, S. Kumar, G. Majumder, K. Mazumdar, S. Mukherjee 

Indian Institute of Science Education and Research (IISER), Pune, India

K. Alpana, S. Dube , B. Kansal, A. Laha, S. Pandey , A. Rastogi , S. Sharma 

Isfahan University of Technology, Isfahan, Iran

H. Bakhshiansohi⁴⁰ , E. Khazaie, M. Zeinali⁴¹

Institute for Research in Fundamental Sciences (IPM), Tehran, Iran

S. Chenarani⁴², S.M. Etesami , M. Khakzad , M. Mohammadi Najafabadi 

University College Dublin, Dublin, Ireland

M. Grunewald 

INFN Sezione di Bari ^a, Bari, Italy, Università di Bari ^b, Bari, Italy, Politecnico di Bari ^c, Bari, Italy

M. Abbrescia^{a,b} , R. Aly^{a,b,43} , C. Aruta^{a,b}, A. Colaleo^a , D. Creanza^{a,c} , N. De Filippis^{a,c} , M. De Palma^{a,b} , A. Di Florio^{a,b}, A. Di Pilato^{a,b} , W. Elmetenawee^{a,b} , L. Fiore^a , A. Gelmi^{a,b} , M. Gul^a , G. Iaselli^{a,c} , M. Ince^{a,b} , S. Lezki^{a,b} , G. Maggi^{a,c} , M. Maggi^a , I. Margjeka^{a,b}, V. Mastrapasqua^{a,b} , S. My^{a,b} , S. Nuzzo^{a,b} , A. Pellecchia^{a,b}, A. Pompili^{a,b} , G. Pugliese^{a,c} , D. Ramos^a, A. Ranieri^a , G. Selvaggi^{a,b} , L. Silvestris^a , F.M. Simone^{a,b} , Ü. Sözbilir^a, R. Venditti^a , P. Verwilligen^a

INFN Sezione di Bologna ^a, Bologna, Italy, Università di Bologna ^b, Bologna, Italy

G. Abbiendi^a , C. Battilana^{a,b} , D. Bonacorsi^{a,b} , L. Borgonovi^a, L. Brigliadori^a, R. Campanini^{a,b} , P. Capiluppi^{a,b} , A. Castro^{a,b} , F.R. Cavallo^a , M. Cuffiani^{a,b} , G.M. Dallavalle^a , T. Diotalevi^{a,b} , F. Fabbri^a , A. Fanfani^{a,b} , P. Giacomelli^a , L. Giommi^{a,b} , C. Grandi^a , L. Guiducci^{a,b}, S. Lo Meo^{a,44}, L. Lunerti^{a,b}, S. Marcellini^a , G. Masetti^a , F.L. Navarreria^{a,b} , A. Perrotta^a , F. Primavera^{a,b} , A.M. Rossi^{a,b} , T. Rovelli^{a,b} , G.P. Siroli^{a,b}

INFN Sezione di Catania ^a, Catania, Italy, Università di Catania ^b, Catania, Italy

S. Albergo^{a,b,45} , S. Costa^{a,b,45} , A. Di Mattia^a , R. Potenza^{a,b}, A. Tricomi^{a,b,45} , C. Tuve^{a,b} 

INFN Sezione di Firenze ^a, Firenze, Italy, Università di Firenze ^b, Firenze, Italy

G. Barbagli^a , A. Cassese^a , R. Ceccarelli^{a,b}, V. Ciulli^{a,b} , C. Civinini^a , R. D'Alessandro^{a,b} , E. Focardi^{a,b} , G. Latino^{a,b} , P. Lenzi^{a,b} , M. Lizzo^{a,b}, M. Meschini^a , S. Paoletti^a , R. Seidita^{a,b}, G. Sguazzoni^a , L. Viliani^a 

INFN Laboratori Nazionali di Frascati, Frascati, Italy

L. Benussi , S. Bianco , D. Piccolo 

INFN Sezione di Genova ^a, Genova, Italy, Università di Genova ^b, Genova, Italy

M. Bozzo^{a,b} , F. Ferro^a , R. Mulargia^{a,b}, E. Robutti^a , S. Tosi^{a,b} 

INFN Sezione di Milano-Bicocca ^a, Milano, Italy, Università di Milano-Bicocca ^b, Milano, Italy

A. Benaglia^a , G. Boldrini , F. Brivio^{a,b}, F. Cetorelli^{a,b}, F. De Guio^{a,b} , M.E. Dinardo^{a,b} , P. Dini^a , S. Gennai^a , A. Ghezzi^{a,b} , P. Govoni^{a,b} , L. Guzzi^{a,b} , M.T. Lucchini^{a,b} , M. Malberti^a, S. Malvezzi , A. Massironi^a , D. Menasce^a , L. Moroni^a , M. Paganoni^{a,b} , D. Pedrini^a , B.S. Pinolini, S. Ragazzi^{a,b} , N. Redaelli^a , T. Tabarelli de Fatis^{a,b} , D. Valsecchi^{a,b,21}, D. Zuolo^{a,b}

INFN Sezione di Napoli ^a, Napoli, Italy, Università di Napoli 'Federico II' ^b, Napoli, Italy, Università della Basilicata ^c, Potenza, Italy, Università G. Marconi ^d, Roma, Italy

S. Buontempo^a , F. Carnevali^{a,b}, N. Cavallo^{a,c} , A. De Iorio^{a,b} , F. Fabozzi^{a,c} , A.O.M. Iorio^{a,b} , L. Lista^{a,b,46} , S. Meola^{a,d,21} , P. Paolucci^{a,21} , B. Rossi^a , C. Sciacca^{a,b} 

INFN Sezione di Padova ^a, Padova, Italy, Università di Padova ^b, Padova, Italy, Università

di Trento ^c, Trento, Italy

P. Azzi^a , N. Bacchetta^a , D. Bisello^{a,b} , P. Bortignon^a , A. Bragagnolo^{a,b} , R. Carlin^{a,b} , P. Checchia^a , T. Dorigo^a , U. Dosselli^a , F. Gasparini^{a,b} , U. Gasparini^{a,b} , G. Grossi, S.Y. Hoh^{a,b} , L. Layer^{a,47}, E. Lusiani , M. Margoni^{a,b} , A.T. Meneguzzo^{a,b} , J. Pazzini^{a,b} , P. Ronchese^{a,b} , R. Rossin^{a,b} , F. Simonetto^{a,b} , G. Strong^a , M. Tosi^{a,b} , H. Yarar^{a,b}, M. Zanetti^{a,b} , P. Zotto^{a,b} , A. Zucchetta^{a,b} , G. Zumerle^{a,b}

INFN Sezione di Pavia ^a, Pavia, Italy, Università di Pavia ^b, Pavia, Italy

C. Aimè^{a,b}, A. Braghieri^a , S. Calzaferri^{a,b}, D. Fiorina^{a,b} , P. Montagna^{a,b}, S.P. Ratti^{a,b}, V. Re^a , C. Riccardi^{a,b} , P. Salvini^a , I. Vai^a , P. Vitulò^{a,b} 

INFN Sezione di Perugia ^a, Perugia, Italy, Università di Perugia ^b, Perugia, Italy

P. Asenov^{a,48} , G.M. Bilei^a , D. Ciangottini^{a,b} , L. Fanò^{a,b} , M. Magherini^b, G. Mantovani^{a,b}, V. Mariani^{a,b}, M. Menichelli^a , F. Moscatelli^{a,48} , A. Piccinelli^{a,b} , M. Presilla^{a,b} , A. Rossi^{a,b} , A. Santocchia^{a,b} , D. Spiga^a , T. Tedeschi^{a,b} 

INFN Sezione di Pisa ^a, Pisa, Italy, Università di Pisa ^b, Pisa, Italy, Scuola Normale Superiore di Pisa ^c, Pisa, Italy, Università di Siena ^d, Siena, Italy

P. Azzurri^a , G. Bagliesi^a , V. Bertacchi^{a,c} , L. Bianchini^a , T. Boccali^a , E. Bossini^{a,b} , R. Castaldi^a , M.A. Ciocci^{a,b} , V. D'Amante^{a,d} , R. Dell'Orso^a , M.R. Di Domenico^{a,d} , S. Donato^a , A. Giassi^a , F. Ligabue^{a,c} , E. Manca^{a,c} , G. Mandorli^{a,c} , D. Matos Figueiredo, A. Messineo^{a,b} , F. Palla^a , S. Parolia^{a,b}, G. Ramirez-Sánchez^{a,c}, A. Rizzi^{a,b} , G. Rolandi^{a,c} , S. Roy Chowdhury^{a,c}, A. Scribano^a, N. Shafiei^{a,b} , P. Spagnolo^a , R. Tenchini^a , G. Tonelli^{a,b} , N. Turini^{a,d} , A. Venturi^a , P.G. Verdini^a

INFN Sezione di Roma ^a, Rome, Italy, Sapienza Università di Roma ^b, Rome, Italy

P. Barria^a , M. Campana^{a,b}, F. Cavallari^a , D. Del Re^{a,b} , E. Di Marco^a , M. Diemoz^a , E. Longo^{a,b} , P. Meridiani^a , G. Organtini^{a,b} , F. Pandolfi^a, R. Paramatti^{a,b} , C. Quaranta^{a,b}, S. Rahatlou^{a,b} , C. Rovelli^a , F. Santanastasio^{a,b} , L. Soffi^a , R. Tramontano^{a,b}

INFN Sezione di Torino ^a, Torino, Italy, Università di Torino ^b, Torino, Italy, Università del Piemonte Orientale ^c, Novara, Italy

N. Amapane^{a,b} , R. Arcidiacono^{a,c} , S. Argiro^{a,b} , M. Arneodo^{a,c} , N. Bartosik^a , R. Bellan^{a,b} , A. Bellora^{a,b} , J. Berenguer Antequera^{a,b} , C. Biino^a , N. Cartiglia^a , M. Costa^{a,b} , R. Covarelli^{a,b} , N. Demaria^a , B. Kiani^{a,b} , F. Legger^a , C. Mariotti^a , S. Maselli^a , E. Migliore^{a,b} , E. Monteil^{a,b} , M. Monteno^a , M.M. Obertino^{a,b} , G. Ortona^a , L. Pacher^{a,b} , N. Pastrone^a , M. Pelliccioni^a , M. Ruspa^{a,c} , K. Shchelina^a , F. Siviero^{a,b} , V. Sola^a , A. Solano^{a,b} , D. Soldi^{a,b} , A. Staiano^a , M. Tornago^{a,b}, D. Trocino^a , A. Vagnerini^{a,b}

INFN Sezione di Trieste ^a, Trieste, Italy, Università di Trieste ^b, Trieste, Italy

S. Belforte^a , V. Candelise^{a,b} , M. Casarsa^a , F. Cossutti^a , A. Da Rold^{a,b} , G. Della Ricca^{a,b} , G. Sorrentino^{a,b}, F. Vazzoler^{a,b} 

Kyungpook National University, Daegu, Korea

S. Dogra , C. Huh , B. Kim, D.H. Kim , G.N. Kim , J. Kim, J. Lee, S.W. Lee , C.S. Moon , Y.D. Oh , S.I. Pak, S. Sekmen , Y.C. Yang

Chonnam National University, Institute for Universe and Elementary Particles, Kwangju, Korea

H. Kim , D.H. Moon 

Hanyang University, Seoul, Korea

B. Francois , T.J. Kim , J. Park 

Korea University, Seoul, Korea

S. Cho, S. Choi , B. Hong , K. Lee, K.S. Lee , J. Lim, J. Park, S.K. Park, J. Yoo

Kyung Hee University, Department of Physics, Seoul, Republic of Korea, Seoul, Korea

J. Goh , A. Gurtu

Sejong University, Seoul, Korea

H.S. Kim , Y. Kim

Seoul National University, Seoul, Korea

J. Almond, J.H. Bhyun, J. Choi, S. Jeon, J. Kim, J.S. Kim, S. Ko, H. Kwon, H. Lee , S. Lee, B.H. Oh, M. Oh , S.B. Oh, H. Seo , U.K. Yang, I. Yoon 

University of Seoul, Seoul, Korea

W. Jang, D.Y. Kang, Y. Kang, S. Kim, B. Ko, J.S.H. Lee , Y. Lee, J.A. Merlin, I.C. Park, Y. Roh, M.S. Ryu, D. Song, I.J. Watson , S. Yang

Yonsei University, Department of Physics, Seoul, Korea

S. Ha, H.D. Yoo

Sungkyunkwan University, Suwon, Korea

M. Choi, H. Lee, Y. Lee, I. Yu 

College of Engineering and Technology, American University of the Middle East (AUM), Egaila, Kuwait, Dasman, Kuwait

T. Beyrouthy, Y. Maghrbi

Riga Technical University, Riga, Latvia

K. Dreimanis , V. Veckalns⁴⁹ 

Vilnius University, Vilnius, Lithuania

M. Ambrozas, A. Carvalho Antunes De Oliveira , A. Juodagalvis , A. Rinkevicius , G. Tamulaitis 

National Centre for Particle Physics, Universiti Malaya, Kuala Lumpur, Malaysia

N. Bin Norjoharuddeen , W.A.T. Wan Abdullah, M.N. Yusli, Z. Zolkapli

Universidad de Sonora (UNISON), Hermosillo, Mexico

J.F. Benitez , A. Castaneda Hernandez , M. León Coello, J.A. Murillo Quijada , A. Sehrawat, L. Valencia Palomo 

Centro de Investigacion y de Estudios Avanzados del IPN, Mexico City, Mexico

G. Ayala, H. Castilla-Valdez, E. De La Cruz-Burelo , I. Heredia-De La Cruz⁵⁰ , R. Lopez-Fernandez, C.A. Mondragon Herrera, D.A. Perez Navarro, A. Sánchez Hernández 

Universidad Iberoamericana, Mexico City, Mexico

S. Carrillo Moreno, C. Oropeza Barrera , F. Vazquez Valencia

Benemerita Universidad Autonoma de Puebla, Puebla, Mexico

I. Pedraza, H.A. Salazar Ibarguen, C. Uribe Estrada

University of Montenegro, Podgorica, Montenegro

J. Mijuskovic⁵¹, N. Raicevic

University of Auckland, Auckland, New Zealand

D. Kofcheck 

University of Canterbury, Christchurch, New Zealand

P.H. Butler 

National Centre for Physics, Quaid-I-Azam University, Islamabad, Pakistan

A. Ahmad, M.I. Asghar, A. Awais, M.I.M. Awan, H.R. Hoorani, W.A. Khan, M.A. Shah, M. Shoaib , M. Waqas 

AGH University of Science and Technology Faculty of Computer Science, Electronics and Telecommunications, Krakow, Poland

V. Avati, L. Grzanka, M. Malawski

National Centre for Nuclear Research, Swierk, Poland

H. Bialkowska, M. Bluj , B. Boimska , M. Górska, M. Kazana, M. Szleper , P. Zalewski

Institute of Experimental Physics, Faculty of Physics, University of Warsaw, Warsaw, Poland

K. Bunkowski, K. Doroba, A. Kalinowski , M. Konecki , J. Krolikowski 

Laboratório de Instrumentação e Física Experimental de Partículas, Lisboa, Portugal

M. Araujo, P. Bargassa , D. Bastos, A. Boletti , P. Faccioli , M. Gallinaro , J. Hollar , N. Leonardo , T. Niknejad, M. Pisano, J. Seixas , O. Toldaiev , J. Varela 

Joint Institute for Nuclear Research, Dubna, Russia

S. Afanasiev, D. Budkouski, I. Golutvin, I. Gorbunov , V. Karjavine, V. Korenkov , A. Lanev, A. Malakhov, V. Matveev^{52,53}, V. Palichik, V. Perelygin, M. Savina, D. Seitova, V. Shalaev, S. Shmatov, S. Shulha, V. Smirnov, O. Teryaev, N. Voitishin, B.S. Yuldashev⁵⁴, A. Zarubin, I. Zhizhin

Petersburg Nuclear Physics Institute, Gatchina (St. Petersburg), Russia

G. Gavrilov , V. Golovtcov, Y. Ivanov, V. Kim⁵⁵ , E. Kuznetsova⁵⁶ , V. Murzin, V. Oreshkin, I. Smirnov, D. Sosnov , V. Sulimov, L. Uvarov, S. Volkov, A. Vorobyev

Institute for Nuclear Research, Moscow, Russia

Yu. Andreev , A. Dermenev, S. Glinenko , N. Golubev, A. Karneyeu , D. Kirpichnikov , M. Kirsanov, N. Krasnikov, A. Pashenkov, G. Pivovarov , A. Toropin

Institute for Theoretical and Experimental Physics named by A.I. Alikhanov of NRC 'Kurchatov Institute', Moscow, Russia

V. Epshteyn, V. Gavrilov, N. Lychkovskaya, A. Nikitenko⁵⁷, V. Popov, A. Stepennov, M. Toms, E. Vlasov , A. Zhokin

Moscow Institute of Physics and Technology, Moscow, Russia

T. Aushev

National Research Nuclear University 'Moscow Engineering Physics Institute' (MEPhI), Moscow, Russia

O. Bychkova, R. Chistov⁵⁸ , M. Danilov⁵⁸ , A. Oskin, P. Parygin, S. Polikarpov⁵⁸ 

P.N. Lebedev Physical Institute, Moscow, Russia

V. Andreev, M. Azarkin, I. Dremin , M. Kirakosyan, A. Terkulov

Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia

A. Belyaev, E. Boos , M. Dubinin⁵⁹ , L. Dudko , A. Ershov, A. Gribushin, V. Klyukhin , O. Kodolova , I. Lokhtin , S. Obraztsov, S. Petrushanko, V. Savrin, A. Snigirev 

Novosibirsk State University (NSU), Novosibirsk, Russia

V. Blinov⁶⁰, T. Dimova⁶⁰, L. Kardapoltsev⁶⁰, A. Kozyrev⁶⁰, I. Ovtin⁶⁰, O. Radchenko⁶⁰, Y. Skovpen⁶⁰ 

Institute for High Energy Physics of National Research Centre 'Kurchatov Institute', Protvino, Russia

I. Azhgirey , I. Bayshev, D. Elumakhov, V. Kachanov, D. Konstantinov , P. Mandrik , V. Petrov, R. Ryutin, S. Slabospitskii , A. Sobol, S. Troshin , N. Tyurin, A. Uzunian, A. Volkov

National Research Tomsk Polytechnic University, Tomsk, Russia

A. Babaev, V. Okhotnikov

Tomsk State University, Tomsk, Russia

V. Borshch, V. Ivanchenko , E. Tcherniaev 

University of Belgrade: Faculty of Physics and VINCA Institute of Nuclear Sciences, Belgrade, Serbia

P. Adzic⁶¹ , M. Dordevic , P. Milenovic , J. Milosevic 

Centro de Investigaciones Energéticas Medioambientales y Tecnológicas (CIEMAT), Madrid, Spain

M. Aguilar-Benitez, J. Alcaraz Maestre , A. Álvarez Fernández, I. Bachiller, M. Barrio Luna, Cristina F. Bedoya , C.A. Carrillo Montoya , M. Cepeda , M. Cerrada, N. Colino , B. De La Cruz, A. Delgado Peris , J.P. Fernández Ramos , J. Flix , M.C. Fouz , O. Gonzalez Lopez , S. Goy Lopez , J.M. Hernandez , M.I. Josa , J. León Holgado , D. Moran, Á. Navarro Tobar , C. Perez Dengra, A. Pérez-Calero Yzquierdo , J. Puerta Pelayo , I. Redondo , L. Romero, S. Sánchez Navas, L. Urda Gómez , C. Willmott

Universidad Autónoma de Madrid, Madrid, Spain

J.F. de Trocóniz, R. Reyes-Almanza 

Universidad de Oviedo, Instituto Universitario de Ciencias y Tecnologías Espaciales de Asturias (ICTEA), Oviedo, Spain

B. Alvarez Gonzalez , J. Cuevas , C. Erice , J. Fernandez Menendez , S. Folgueras , I. Gonzalez Caballero , J.R. González Fernández, E. Palencia Cortezon , C. Ramón Álvarez, V. Rodríguez Bouza , A. Soto Rodríguez, A. Trapote, N. Trevisani , C. Vico Villalba

Instituto de Física de Cantabria (IFCA), CSIC-Universidad de Cantabria, Santander, Spain

J.A. Brochero Cifuentes , I.J. Cabrillo, A. Calderon , J. Duarte Campderros , M. Fernández , C. Fernandez Madrazo , P.J. Fernández Manteca , A. García Alonso, G. Gomez, C. Martinez Rivero, P. Martinez Ruiz del Arbol , F. Matorras , P. Matorras Cuevas , J. Piedra Gomez , C. Prieels, A. Ruiz-Jimeno , L. Scodellaro , I. Vila, J.M. Vizan Garcia 

University of Colombo, Colombo, Sri Lanka

M.K. Jayananda, B. Kailasapathy⁶², D.U.J. Sonnadara, D.D.C. Wickramarathna

University of Ruhuna, Department of Physics, Matara, Sri Lanka

W.G.D. Dharmaratna , K. Liyanage, N. Perera, N. Wickramage

CERN, European Organization for Nuclear Research, Geneva, Switzerland

T.K. Arrestad , D. Abbaneo, J. Alimena , E. Auffray, G. Auzinger, J. Baechler, P. Baillon[†], D. Barney , J. Bendavid, M. Bianco , A. Bocci , C. Caillol, T. Camporesi, M. Capeans Garrido , G. Cerminara, N. Chernyavskaya , S.S. Chhibra , M. Cipriani , L. Cristella , D. d'Enterria , A. Dabrowski , A. David , A. De Roeck , M.M. Defranchis , M. Deile , M. Dobson, M. Dünser , N. Dupont, A. Elliott-Peisert, N. Emriskova, F. Fallavollita⁶³,

A. Florent , L. Forthomme , G. Franzoni , W. Funk, S. Giani, D. Gigi, K. Gill, F. Glege, L. Gouskos , M. Haranko , J. Hegeman , V. Innocente , T. James, P. Janot , J. Kaspar , J. Kieseler , M. Komm , N. Kratochwil, C. Lange , S. Laurila, P. Lecoq , A. Lintuluoto, K. Long , C. Lourenço , B. Maier, L. Malgeri , S. Mallios, M. Mannelli, A.C. Marini , F. Meijers, S. Mersi , E. Meschi , F. Moortgat , M. Mulders , S. Orfanelli, L. Orsini, F. Pantaleo , E. Perez, M. Peruzzi , A. Petrilli, G. Petrucciani , A. Pfeiffer , M. Pierini , D. Piparo, M. Pitt , H. Qu , T. Quast, D. Rabady , A. Racz, G. Reales Gutiérrez, M. Rovere, H. Sakulin, J. Salfeld-Nebgen , S. Scarfi, C. Schäfer, C. Schwick, M. Selvaggi , A. Sharma, P. Silva , W. Snoeys , P. Sphicas⁶⁴ , S. Summers , K. Tatar , V.R. Tavolaro , D. Treille, P. Tropea, A. Tsirou, G.P. Van Onsem , J. Wanczyk⁶⁵, K.A. Wozniak, W.D. Zeuner

Paul Scherrer Institut, Villigen, Switzerland

L. Caminada⁶⁶ , A. Ebrahimi , W. Erdmann, R. Horisberger, Q. Ingram, H.C. Kaestli, D. Kotlinski, U. Langenegger, M. Missiroli⁶⁶ , L. Noehte⁶⁶, T. Rohe

ETH Zurich - Institute for Particle Physics and Astrophysics (IPA), Zurich, Switzerland

K. Androsov⁶⁵ , M. Backhaus , P. Berger, A. Calandri , A. De Cosa, G. Dissertori , M. Dittmar, M. Donegà, C. Dorfer , F. Eble, K. Gedia, F. Glessgen, T.A. Gómez Espinosa , C. Grab , D. Hits, W. Lustermann, A.-M. Lyon, R.A. Manzoni , L. Marchese , C. Martin Perez, M.T. Meinhard, F. Nessi-Tedaldi, J. Niedziela , F. Pauss, V. Perovic, S. Pigazzini , M.G. Ratti , M. Reichmann, C. Reissel, T. Reitenspiess, B. Ristic , D. Ruini, D.A. Sanz Becerra , V. Stampf, J. Steggemann⁶⁵ , R. Wallny , D.H. Zhu

Universität Zürich, Zurich, Switzerland

C. Amsler⁶⁷ , P. Bärtschi, C. Botta , D. Brzhechko, M.F. Canelli , K. Cormier, A. De Wit , R. Del Burgo, J.K. Heikkilä , M. Huwiler, W. Jin, A. Jofrehei , B. Kilminster , S. Leontsinis , S.P. Liechti, A. Macchiolo , P. Meiring, V.M. Mikuni , U. Molinatti, I. Neutelings, A. Reimers, P. Robmann, S. Sanchez Cruz , K. Schweiger , M. Senger, Y. Takahashi 

National Central University, Chung-Li, Taiwan

C. Adloff⁶⁸, C.M. Kuo, W. Lin, A. Roy , T. Sarkar³⁸ , S.S. Yu

National Taiwan University (NTU), Taipei, Taiwan

L. Ceard, Y. Chao, K.F. Chen , P.H. Chen , P.s. Chen, H. Cheng , W.-S. Hou , Y.y. Li, R.-S. Lu, E. Paganis , A. Psallidas, A. Steen, H.y. Wu, E. Yazgan , P.r. Yu

Chulalongkorn University, Faculty of Science, Department of Physics, Bangkok, Thailand

B. Asavapibhop , C. Asawatangtrakuldee , N. Srimanobhas 

Çukurova University, Physics Department, Science and Art Faculty, Adana, Turkey

F. Boran , S. Damarseckin⁶⁹, Z.S. Demiroglu , F. Dolek , I. Dumanoglu⁷⁰ , E. Eskut, Y. Guler⁷¹ , E. Gurpinar Guler⁷¹ , C. Isik, O. Kara, A. Kayis Topaksu, U. Kiminsu , G. Onengut, K. Ozdemir⁷², A. Polatoz, A.E. Simsek , B. Tali⁷³, U.G. Tok , S. Turkcapar, I.S. Zorbakir 

Middle East Technical University, Physics Department, Ankara, Turkey

B. Isildak⁷⁴, G. Karapinar, K. Ocalan⁷⁵ , M. Yalvac⁷⁶ 

Bogazici University, Istanbul, Turkey

B. Akgun, I.O. Atakisi , E. Gülmез , M. Kaya⁷⁷ , O. Kaya⁷⁸, Ö. Özçelik, S. Tekten⁷⁹, E.A. Yetkin⁸⁰ 

Istanbul Technical University, Istanbul, Turkey

A. Cakir , K. Cankocak⁷⁰ , Y. Komurcu, S. Sen⁸¹ 

Istanbul University, Istanbul, Turkey

S. Cerci⁷³, I. Hos⁸², B. Kaynak, S. Ozkorucuklu, H. Sert , D. Sunar Cerci⁷³ , C. Zorbilmez

Institute for Scintillation Materials of National Academy of Science of Ukraine, Kharkov, Ukraine

B. Grynyov

National Scientific Center, Kharkov Institute of Physics and Technology, Kharkov, Ukraine

L. Levchuk 

University of Bristol, Bristol, United Kingdom

D. Anthony, E. Bhal , S. Bologna, J.J. Brooke , A. Bundock , E. Clement , D. Cussans , H. Flacher , J. Goldstein , G.P. Heath, H.F. Heath , L. Kreczko , B. Krikler , S. Paramesvaran, S. Seif El Nasr-Storey, V.J. Smith, N. Stylianou⁸³ , K. Walkingshaw Pass, R. White

Rutherford Appleton Laboratory, Didcot, United Kingdom

K.W. Bell, A. Belyaev⁸⁴ , C. Brew , R.M. Brown, D.J.A. Cockerill, C. Cooke, K.V. Ellis, K. Harder, S. Harper, M.-L. Holmberg⁸⁵, J. Linacre , K. Manolopoulos, D.M. Newbold , E. Olaiya, D. Petyt, T. Reis , T. Schuh, C.H. Shepherd-Themistocleous, I.R. Tomalin, T. Williams 

Imperial College, London, United Kingdom

R. Bainbridge , P. Bloch , S. Bonomally, J. Borg , S. Breeze, O. Buchmuller, V. Cepaitis , G.S. Chahal⁸⁶ , D. Colling, P. Dauncey , G. Davies , M. Della Negra , S. Fayer, G. Fedi , G. Hall , M.H. Hassanshahi, G. Iles, J. Langford, L. Lyons, A.-M. Magnan, S. Malik, A. Martelli , D.G. Monk, J. Nash⁸⁷ , M. Pesaresi, B.C. Radburn-Smith, D.M. Raymond, A. Richards, A. Rose, E. Scott , C. Seez, A. Shtipliyski, A. Tapper , K. Uchida, T. Virdee²¹ , M. Vojinovic , N. Wardle , S.N. Webb , D. Winterbottom

Brunel University, Uxbridge, United Kingdom

K. Coldham, J.E. Cole , A. Khan, P. Kyberd , I.D. Reid , L. Teodorescu, S. Zahid 

Baylor University, Waco, Texas, USA

S. Abdullin , A. Brinkerhoff , B. Caraway , J. Dittmann , K. Hatakeyama , A.R. Kanuganti, B. McMaster , N. Pastika, M. Saunders , S. Sawant, C. Sutantawibul, J. Wilson 

Catholic University of America, Washington, DC, USA

R. Bartek , A. Dominguez , R. Uniyal , A.M. Vargas Hernandez

The University of Alabama, Tuscaloosa, Alabama, USA

A. Buccilli , S.I. Cooper , D. Di Croce , S.V. Gleyzer , C. Henderson , C.U. Perez , P. Rumerio⁸⁸ , C. West 

Boston University, Boston, Massachusetts, USA

A. Akpinar , A. Albert , D. Arcaro , C. Cosby , Z. Demiragli , E. Fontanesi, D. Gastler, S. May , J. Rohlf , K. Salyer , D. Sperka, D. Spitzbart , I. Suarez , A. Tsatsos, S. Yuan, D. Zou

Brown University, Providence, Rhode Island, USA

G. Benelli , B. Burkle , X. Coubez²², D. Cutts , M. Hadley , U. Heintz , J.M. Hogan⁸⁹ , T. KWON, G. Landsberg , K.T. Lau , D. Li, M. Lukasik, J. Luo , M. Narain, N. Pervan,

S. Sagir⁹⁰ , F. Simpson, E. Usai , W.Y. Wong, X. Yan , D. Yu , W. Zhang

University of California, Davis, Davis, California, USA

J. Bonilla , C. Brainerd , R. Breedon, M. Calderon De La Barca Sanchez, M. Chertok , J. Conway , P.T. Cox, R. Erbacher, G. Haza, F. Jensen , O. Kukral, R. Lander, M. Mulhearn , D. Pellett, B. Regnery , D. Taylor , Y. Yao , F. Zhang 

University of California, Los Angeles, California, USA

M. Bachtis , R. Cousins , A. Datta , D. Hamilton, J. Hauser , M. Ignatenko, M.A. Iqbal, T. Lam, W.A. Nash, S. Regnard , D. Saltzberg , B. Stone, V. Valuev 

University of California, Riverside, Riverside, California, USA

K. Burt, Y. Chen, R. Clare , J.W. Gary , M. Gordon, G. Hanson , G. Karapostoli , O.R. Long , N. Manganelli, M. Olmedo Negrete, W. Si , S. Wimpenny, Y. Zhang

University of California, San Diego, La Jolla, California, USA

J.G. Branson, P. Chang , S. Cittolin, S. Cooperstein , N. Deelen , D. Diaz , J. Duarte , R. Gerosa , L. Giannini , J. Guiang, R. Kansal , V. Krutelyov , R. Lee, J. Letts , M. Masciovecchio , F. Mokhtar, M. Pieri , B.V. Sathia Narayanan , V. Sharma , M. Tadel, A. Vartak , F. Würthwein , Y. Xiang , A. Yagil 

University of California, Santa Barbara - Department of Physics, Santa Barbara, California, USA

N. Amin, C. Campagnari , M. Citron , A. Dorsett, V. Dutta , J. Incandela , M. Kilpatrick , J. Kim , B. Marsh, H. Mei, M. Oshiro, M. Quinnan , J. Richman, U. Sarica , F. Setti, J. Sheplock, P. Siddireddy, D. Stuart, S. Wang 

California Institute of Technology, Pasadena, California, USA

A. Bornheim , O. Cerri, I. Dutta , J.M. Lawhorn , N. Lu , J. Mao, H.B. Newman , T.Q. Nguyen , M. Spiropulu , J.R. Vlimant , C. Wang , S. Xie , Z. Zhang , R.Y. Zhu 

Carnegie Mellon University, Pittsburgh, Pennsylvania, USA

J. Alison , S. An , M.B. Andrews, P. Bryant , T. Ferguson , A. Harilal, C. Liu, T. Mudholkar , M. Paulini , A. Sanchez, W. Terrill

University of Colorado Boulder, Boulder, Colorado, USA

J.P. Cumalat , W.T. Ford , A. Hassani, G. Karathanasis, E. MacDonald, R. Patel, A. Perloff , C. Savard, K. Stenson , K.A. Ulmer , S.R. Wagner 

Cornell University, Ithaca, New York, USA

J. Alexander , S. Bright-Thonney , X. Chen , Y. Cheng , D.J. Cranshaw , S. Hogan, J. Monroy , J.R. Patterson , D. Quach , J. Reichert , M. Reid , A. Ryd, W. Sun , J. Thom , P. Wittich , R. Zou 

Fermi National Accelerator Laboratory, Batavia, Illinois, USA

M. Albrow , M. Alyari , G. Apollinari, A. Apresyan , A. Apyan , L.A.T. Bauerdtick , D. Berry , J. Berryhill , P.C. Bhat, K. Burkett , J.N. Butler, A. Canepa, G.B. Cerati , H.W.K. Cheung , F. Chlebana, K.F. Di Petrillo , V.D. Elvira , Y. Feng, J. Freeman, Z. Gecse, L. Gray, D. Green, S. Grünendahl , O. Gutsche , R.M. Harris , R. Heller, T.C. Herwig , J. Hirschauer , B. Jayatilaka , S. Jindariani, M. Johnson, U. Joshi, T. Klijsma , B. Klima , K.H.M. Kwok, S. Lammel , D. Lincoln , R. Lipton, T. Liu, C. Madrid, K. Maeshima, C. Mantilla , D. Mason, P. McBride , P. Merkel, S. Mrenna , S. Nahn , J. Ngadiuba , V. O'Dell, V. Papadimitriou, K. Pedro , C. Pena⁵⁹ , O. Prokofyev, F. Ravera , A. Reinsvold Hall , L. Ristori , E. Sexton-Kennedy , N. Smith , A. Soha 

L. Spiegel, S. Stoynev [ID](#), J. Strait [ID](#), L. Taylor [ID](#), S. Tkaczyk, N.V. Tran [ID](#), L. Uplegger [ID](#), E.W. Vaandering [ID](#), H.A. Weber [ID](#)

University of Florida, Gainesville, Florida, USA

D. Acosta [ID](#), P. Avery, D. Bourilkov [ID](#), L. Cadamuro [ID](#), V. Cherepanov, F. Errico [ID](#), R.D. Field, D. Guerrero, B.M. Joshi [ID](#), M. Kim, E. Koenig, J. Konigsberg [ID](#), A. Korytov, K.H. Lo, K. Matchev [ID](#), N. Menendez [ID](#), G. Mitselmakher [ID](#), A. Muthirakalayil Madhu, N. Rawal, D. Rosenzweig, S. Rosenzweig, J. Rotter, K. Shi [ID](#), J. Wang [ID](#), E. Yigitbasi [ID](#), X. Zuo

Florida State University, Tallahassee, Florida, USA

T. Adams [ID](#), A. Askew [ID](#), R. Habibullah [ID](#), V. Hagopian, K.F. Johnson, R. Khurana, T. Kolberg [ID](#), G. Martinez, H. Prosper [ID](#), C. Schiber, O. Viazlo [ID](#), R. Yohay [ID](#), J. Zhang

Florida Institute of Technology, Melbourne, Florida, USA

M.M. Baarmann [ID](#), S. Butalla, T. Elkafrawy¹⁶ [ID](#), M. Hohlmann [ID](#), R. Kumar Verma [ID](#), D. Noonan [ID](#), M. Rahmani, F. Yumiceva [ID](#)

University of Illinois at Chicago (UIC), Chicago, Illinois, USA

M.R. Adams, H. Becerril Gonzalez [ID](#), R. Cavanaugh [ID](#), S. Dittmer, O. Evdokimov [ID](#), C.E. Gerber [ID](#), D.A. Hangal [ID](#), D.J. Hofman [ID](#), A.H. Merrit, C. Mills [ID](#), G. Oh [ID](#), T. Roy, S. Rudrabhatla, M.B. Tonjes [ID](#), N. Varelas [ID](#), J. Viinikainen [ID](#), X. Wang, Z. Wu [ID](#), Z. Ye [ID](#)

The University of Iowa, Iowa City, Iowa, USA

M. Alhusseini [ID](#), K. Dilsiz⁹¹ [ID](#), L. Emediato, R.P. Gandrajula [ID](#), O.K. Köseyan [ID](#), J.-P. Merlo, A. Mestvirishvili⁹², J. Nachtman, H. Ogul⁹³ [ID](#), Y. Onel [ID](#), A. Penzo, C. Snyder, E. Tiras⁹⁴ [ID](#)

Johns Hopkins University, Baltimore, Maryland, USA

O. Amram [ID](#), B. Blumenfeld [ID](#), L. Corcodilos [ID](#), J. Davis, M. Eminizer [ID](#), A.V. Gritsan [ID](#), S. Kyriacou, P. Maksimovic [ID](#), J. Roskes [ID](#), M. Swartz, T.Á. Vámi [ID](#)

The University of Kansas, Lawrence, Kansas, USA

A. Abreu, J. Anguiano, C. Baldenegro Barrera [ID](#), P. Baringer [ID](#), A. Bean [ID](#), A. Bylinkin [ID](#), Z. Flowers, T. Isidori, S. Khalil [ID](#), J. King, G. Krintiras [ID](#), A. Kropivnitskaya [ID](#), M. Lazarovits, C. Le Mahieu, C. Lindsey, J. Marquez, N. Minafra [ID](#), M. Murray [ID](#), M. Nickel, C. Rogan [ID](#), C. Royon, R. Salvatico [ID](#), S. Sanders, E. Schmitz, C. Smith [ID](#), J.D. Tapia Takaki [ID](#), Q. Wang [ID](#), Z. Warner, J. Williams [ID](#), G. Wilson [ID](#)

Kansas State University, Manhattan, Kansas, USA

S. Duric, A. Ivanov [ID](#), K. Kaadze [ID](#), D. Kim, Y. Maravin [ID](#), T. Mitchell, A. Modak, K. Nam

Lawrence Livermore National Laboratory, Livermore, California, USA

F. Rebassoo, D. Wright

University of Maryland, College Park, Maryland, USA

E. Adams, A. Baden, O. Baron, A. Belloni [ID](#), S.C. Eno [ID](#), N.J. Hadley [ID](#), S. Jabeen [ID](#), R.G. Kellogg, T. Koeth, Y. Lai, S. Lascio, A.C. Mignerey, S. Nabili, C. Palmer [ID](#), M. Seidel [ID](#), A. Skuja [ID](#), L. Wang, K. Wong [ID](#)

Massachusetts Institute of Technology, Cambridge, Massachusetts, USA

D. Abercrombie, G. Andreassi, R. Bi, W. Busza [ID](#), I.A. Cali, Y. Chen [ID](#), M. D'Alfonso [ID](#), J. Eysermans, C. Freer [ID](#), G. Gomez Ceballos, M. Goncharov, P. Harris, M. Hu, M. Klute [ID](#), D. Kovalskyi [ID](#), J. Krupa, Y.-J. Lee [ID](#), C. Mironov [ID](#), C. Paus [ID](#), D. Rankin [ID](#), C. Roland [ID](#), G. Roland, Z. Shi [ID](#), G.S.F. Stephans [ID](#), J. Wang, Z. Wang [ID](#), B. Wyslouch [ID](#)

University of Minnesota, Minneapolis, Minnesota, USA

R.M. Chatterjee, A. Evans , J. Hiltbrand, Sh. Jain , M. Krohn, Y. Kubota, J. Mans , M. Revering, R. Rusack , R. Saradhy, N. Schroeder , N. Strobbe , M.A. Wadud

University of Nebraska-Lincoln, Lincoln, Nebraska, USA

K. Bloom , M. Bryson, S. Chauhan , D.R. Claes, C. Fangmeier, L. Finco , F. Golf , C. Joo, I. Kravchenko , M. Musich, I. Reed, J.E. Siado, G.R. Snow[†], W. Tabb, F. Yan, A.G. Zecchinelli

State University of New York at Buffalo, Buffalo, New York, USA

G. Agarwal , H. Bandyopadhyay , L. Hay , I. Iashvili , A. Kharchilava, C. McLean , D. Nguyen, J. Pekkanen , S. Rappoccio , A. Williams 

Northeastern University, Boston, Massachusetts, USA

G. Alverson , E. Barberis, Y. Haddad , Y. Han, A. Hortiangtham, A. Krishna, J. Li , G. Madigan, B. Marzocchi , D.M. Morse , V. Nguyen, T. Orimoto , A. Parker, L. Skinnari , A. Tishelman-Charny, T. Wamorkar, B. Wang , A. Wisecarver, D. Wood 

Northwestern University, Evanston, Illinois, USA

S. Bhattacharya , J. Bueghly, Z. Chen , A. Gilbert , T. Gunter , K.A. Hahn, Y. Liu, N. Odell, M.H. Schmitt , M. Velasco

University of Notre Dame, Notre Dame, Indiana, USA

R. Band , R. Bucci, M. Cremonesi, A. Das , N. Dev , R. Goldouzian , M. Hildreth, K. Hurtado Anampa , C. Jessop , K. Lannon , J. Lawrence, N. Loukas , D. Lutton, J. Mariano, N. Marinelli, I. Mcalister, T. McCauley , C. Mcgrady, K. Mohrman, C. Moore, Y. Musienko⁵², R. Ruchti, A. Townsend, M. Wayne, A. Wightman, M. Zarucki , L. Zygala

The Ohio State University, Columbus, Ohio, USA

B. Bylsma, L.S. Durkin , B. Francis , C. Hill , M. Nunez Ornelas , K. Wei, B.L. Winer, B.R. Yates 

Princeton University, Princeton, New Jersey, USA

F.M. Addesa , B. Bonham , P. Das , G. Dezoort, P. Elmer , A. Frankenthal , B. Greenberg , N. Haubrich, S. Higginbotham, A. Kalogeropoulos , G. Kopp, S. Kwan , D. Lange, D. Marlow , K. Mei , I. Ojalvo, J. Olsen , D. Stickland , C. Tully 

University of Puerto Rico, Mayaguez, Puerto Rico, USA

S. Malik , S. Norberg

Purdue University, West Lafayette, Indiana, USA

A.S. Bakshi, V.E. Barnes , R. Chawla , S. Das , L. Gutay, M. Jones , A.W. Jung , S. Karmarkar, D. Kondratyev , A.M. Koshy, M. Liu, G. Negro, N. Neumeister , G. Paspalaki, S. Piperov , A. Purohit, J.F. Schulte , M. Stojanovic¹⁷, J. Thieman , F. Wang , R. Xiao , W. Xie 

Purdue University Northwest, Hammond, Indiana, USA

J. Dolen , N. Parashar

Rice University, Houston, Texas, USA

A. Baty , T. Carnahan, M. Decaro, S. Dildick , K.M. Ecklund , S. Freed, P. Gardner, F.J.M. Geurts , A. Kumar , W. Li, B.P. Padley , R. Redjimi, W. Shi , A.G. Stahl Leiton , S. Yang , L. Zhang⁹⁵, Y. Zhang 

University of Rochester, Rochester, New York, USA

A. Bodek , P. de Barbaro, R. Demina , J.L. Dulemba , C. Fallon, T. Ferbel , M. Galanti, A. Garcia-Bellido , O. Hindrichs , A. Khukhunaishvili, E. Ranken, R. Taus

Rutgers, The State University of New Jersey, Piscataway, New Jersey, USA

B. Chiarito, J.P. Chou , A. Gandrakota , Y. Gershtein , E. Halkiadakis , A. Hart, M. Heindl , O. Karacheban²⁵ , I. Laflotte, A. Lath , R. Montalvo, K. Nash, M. Osherson, S. Salur , S. Schnetzer, S. Somalwar , R. Stone, S.A. Thayil , S. Thomas, H. Wang 

University of Tennessee, Knoxville, Tennessee, USA

H. Acharya, A.G. Delannoy , S. Fiorendi , S. Spanier 

Texas A&M University, College Station, Texas, USA

O. Bouhali⁹⁶ , M. Dalchenko , A. Delgado , R. Eusebi, J. Gilmore, T. Huang, T. Kamon⁹⁷, H. Kim , S. Luo , S. Malhotra, R. Mueller, D. Overton, D. Rathjens , A. Safonov 

Texas Tech University, Lubbock, Texas, USA

N. Akchurin, J. Damgov, V. Hegde, S. Kunori, K. Lamichhane, S.W. Lee , T. Mengke, S. Muthumuni , T. Peltola , I. Volobouev, Z. Wang, A. Whitbeck

Vanderbilt University, Nashville, Tennessee, USA

E. Appelt , S. Greene, A. Gurrola , W. Johns, A. Melo, H. Ni, K. Padeken , F. Romeo , P. Sheldon , S. Tuo, J. Velkovska 

University of Virginia, Charlottesville, Virginia, USA

M.W. Arenton , B. Cardwell, B. Cox , G. Cummings , J. Hakala , R. Hirosky , M. Joyce , A. Ledovskoy , A. Li, C. Neu , C.E. Perez Lara , B. Tannenwald , S. White 

Wayne State University, Detroit, Michigan, USA

N. Poudyal 

University of Wisconsin - Madison, Madison, WI, Wisconsin, USA

S. Banerjee, K. Black , T. Bose , S. Dasu , I. De Bruyn , P. Everaerts , C. Galloni, H. He, M. Herndon , A. Hervé, U. Hussain, A. Lanaro, A. Loeliger, R. Loveless, J. Madhusudanan Sreekala , A. Mallampalli, A. Mohammadi, D. Pinna, A. Savin, V. Shang, V. Sharma , W.H. Smith , D. Teague, S. Trembath-Reichert, W. Vetens 

†: Deceased

1: Also at TU Wien, Wien, Austria

2: Also at Institute of Basic and Applied Sciences, Faculty of Engineering, Arab Academy for Science, Technology and Maritime Transport, Alexandria, Egypt

3: Also at Université Libre de Bruxelles, Bruxelles, Belgium

4: Also at Universidade Estadual de Campinas, Campinas, Brazil

5: Also at Federal University of Rio Grande do Sul, Porto Alegre, Brazil

6: Also at The University of the State of Amazonas, Manaus, Brazil

7: Also at University of Chinese Academy of Sciences, Beijing, China

8: Also at Department of Physics, Tsinghua University, Beijing, China

9: Also at UFMS, Nova Andradina, Brazil

10: Also at Nanjing Normal University Department of Physics, Nanjing, China

11: Now at The University of Iowa, Iowa City, Iowa, USA

12: Also at Institute for Theoretical and Experimental Physics named by A.I. Alikhanov of NRC 'Kurchatov Institute', Moscow, Russia

13: Also at Joint Institute for Nuclear Research, Dubna, Russia

14: Also at Helwan University, Cairo, Egypt

15: Now at Zewail City of Science and Technology, Zewail, Egypt

16: Also at Ain Shams University, Cairo, Egypt

17: Also at Purdue University, West Lafayette, Indiana, USA

- 18: Also at Université de Haute Alsace, Mulhouse, France
19: Also at Tbilisi State University, Tbilisi, Georgia
20: Also at Erzincan Binali Yildirim University, Erzincan, Turkey
21: Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland
22: Also at RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany
23: Also at University of Hamburg, Hamburg, Germany
24: Also at Isfahan University of Technology, Isfahan, Iran
25: Also at Brandenburg University of Technology, Cottbus, Germany
26: Also at Forschungszentrum Jülich, Juelich, Germany
27: Also at Physics Department, Faculty of Science, Assiut University, Assiut, Egypt
28: Also at Karoly Robert Campus, MATE Institute of Technology, Gyongyos, Hungary
29: Also at Institute of Physics, University of Debrecen, Debrecen, Hungary
30: Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary
31: Also at MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary
32: Also at Wigner Research Centre for Physics, Budapest, Hungary
33: Also at IIT Bhubaneswar, Bhubaneswar, India
34: Also at Institute of Physics, Bhubaneswar, India
35: Also at Punjab Agricultural University, Ludhiana, India, Ludhiana, India
36: Also at Shoolini University, Solan, India
37: Also at University of Hyderabad, Hyderabad, India
38: Also at University of Visva-Bharati, Santiniketan, India
39: Also at Indian Institute of Technology (IIT), Mumbai, India
40: Also at Deutsches Elektronen-Synchrotron, Hamburg, Germany
41: Also at Sharif University of Technology, Tehran, Iran
42: Also at Department of Physics, University of Science and Technology of Mazandaran, Behshahr, Iran
43: Now at INFN Sezione di Bari, Università di Bari, Politecnico di Bari, Bari, Italy
44: Also at Italian National Agency for New Technologies, Energy and Sustainable Economic Development, Bologna, Italy
45: Also at Centro Siciliano di Fisica Nucleare e di Struttura Della Materia, Catania, Italy
46: Also at Scuola Superiore Meridionale, Università di Napoli Federico II, Napoli, Italy
47: Also at Università di Napoli 'Federico II', Napoli, Italy
48: Also at Consiglio Nazionale delle Ricerche - Istituto Officina dei Materiali, Perugia, Italy
49: Also at Riga Technical University, Riga, Latvia
50: Also at Consejo Nacional de Ciencia y Tecnología, Mexico City, Mexico
51: Also at IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France
52: Also at Institute for Nuclear Research, Moscow, Russia
53: Now at National Research Nuclear University 'Moscow Engineering Physics Institute' (MEPhI), Moscow, Russia
54: Also at Institute of Nuclear Physics of the Uzbekistan Academy of Sciences, Tashkent, Uzbekistan
55: Also at St. Petersburg State Polytechnical University, St. Petersburg, Russia
56: Also at University of Florida, Gainesville, Florida, USA
57: Also at Imperial College, London, United Kingdom
58: Also at P.N. Lebedev Physical Institute, Moscow, Russia
59: Also at California Institute of Technology, Pasadena, California, USA
60: Also at Budker Institute of Nuclear Physics, Novosibirsk, Russia
61: Also at Faculty of Physics, University of Belgrade, Belgrade, Serbia

- 62: Also at Trincomalee Campus, Eastern University, Sri Lanka, Nilaveli, Sri Lanka
63: Also at INFN Sezione di Pavia, Università di Pavia, Pavia, Italy
64: Also at National and Kapodistrian University of Athens, Athens, Greece
65: Also at Ecole Polytechnique Fédérale Lausanne, Lausanne, Switzerland
66: Also at Universität Zürich, Zurich, Switzerland
67: Also at Stefan Meyer Institute for Subatomic Physics, Vienna, Austria
68: Also at Laboratoire d'Annecy-le-Vieux de Physique des Particules, IN2P3-CNRS, Annecy-le-Vieux, France
69: Also at Şırnak University, Sirnak, Turkey
70: Also at Near East University, Research Center of Experimental Health Science, Nicosia, Turkey
71: Also at Konya Technical University, Konya, Turkey
72: Also at Piri Reis University, Istanbul, Turkey
73: Also at Adiyaman University, Adiyaman, Turkey
74: Also at Ozyegin University, Istanbul, Turkey
75: Also at Necmettin Erbakan University, Konya, Turkey
76: Also at Bozok Universitetesi Rektörlüğü, Yozgat, Turkey
77: Also at Marmara University, Istanbul, Turkey
78: Also at Milli Savunma University, Istanbul, Turkey
79: Also at Kafkas University, Kars, Turkey
80: Also at Istanbul Bilgi University, Istanbul, Turkey
81: Also at Hacettepe University, Ankara, Turkey
82: Also at Istanbul University - Cerrahpasa, Faculty of Engineering, Istanbul, Turkey
83: Also at Vrije Universiteit Brussel, Brussel, Belgium
84: Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom
85: Also at Rutherford Appleton Laboratory, Didcot, United Kingdom
86: Also at IPPP Durham University, Durham, United Kingdom
87: Also at Monash University, Faculty of Science, Clayton, Australia
88: Also at Università di Torino, Torino, Italy
89: Also at Bethel University, St. Paul, Minneapolis, USA
90: Also at Karamanoğlu Mehmetbey University, Karaman, Turkey
91: Also at Bingöl University, Bingöl, Turkey
92: Also at Georgian Technical University, Tbilisi, Georgia
93: Also at Sinop University, Sinop, Turkey
94: Also at Erciyes University, Kayseri, Turkey
95: Also at Institute of Modern Physics and Key Laboratory of Nuclear Physics and Ion-beam Application (MOE) - Fudan University, Shanghai, China
96: Also at Texas A&M University at Qatar, Doha, Qatar
97: Also at Kyungpook National University, Daegu, Korea